SwRI-8707

CONTROL OF HEAVY-DUTY DIESEL PARTICULATE EMISSIONS USING CATALYZED CERAMIC TRAPS

FINAL REPORT

Prepared for
California Air Resources Board
P.O. Box 2815
Sacramento, CA 95812

Under Contract No.
A4-132-32

June 1987

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By
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June 1987

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The Project Officer and the Technical Project Monitor for the ARB during this work were Mr. Robert Grant and Mr. Michael Carter, respectively. SwRI Project Director was Mr. Karl J. Springer, and SwRI Project Manager and Principal Investigator was Mr. Terry L. Ullman. Lead technical personnel were Mr. Jim Chessher, Mr. Keith Echtle, and Mr. Nathan Reeh.

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This report was submitted in fulfillment of ARB Contract No. A4-132-32, "Particulate Trap Demonstration for Heavy-Duty Diesels," by Southwest Research Institute, under sponsorship of the California Air Resources Board. Work was completed as of June 30, 1987.

ABSTRACT

A ceramic particulate filter (trap) was designed as a muffler replacement for application to a GMC RTS II 04 city bus powered by a 2-stroke DDAD 6V-92TAC heavy-duty diesel engine. Preliminary testing indicated that the design was of adequate capacity and filtering efficiency to reduce total particulate by more than 70 percent and eliminate visible smoke emissions. Three different catalyst formulations were applied to three trap units to enhance on-board trap regeneration. Although some balancing of accumulated particulate with regenerated particulate was obtained below 500°C, notable regeneration was not obtained until the catalyzed substrates reached a temperature range of 510 to 550°C. The trap units were located before the turbocharger, where high exhaust temperatures, promoted by creating periodic engine upset, could best be utilized for regeneration. Even though low-temperature regeneration was not observed with any of the three catalyzed traps, all three were able to eliminate visible smoke and reduce total particulate by 80 percent; however, on-board regeneration could only be accomplished through periodic high-load operation of the bus. The durability of these catalyzed traps has yet to be established in field a demonstration because they lack suitable low-temperature regeneration characteristics to permit general use of the bus.

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I. SUMMARY

Heavy-duty diesel vehicles are a major contributor to the NO_x and particulate matter air pollution problems of California. Without further controls, visibility is predicted to further degrade in California due to increased numbers of heavy-duty diesel vehicles.(1)* Diesel transit buses contribute a significant portion of particulate matter to air pollution problems facing the South Coast Air Basin.(2) In addition, bus emissions are of particular concern due to their proximity to urban areas, maximizing population exposure.(3)

The objective of this work was to equip a transit bus with a self-regenerating catalyzed ceramic particulate trap system designed to reduce measured particulate emissions by 70 percent and eliminate visible smoke emissions. The program focused on transferring the concept used for particulate control on the Mercedes light-duty diesel vehicle currently marketed in California to a GMC RTS II heavy-duty diesel transit bus. The Mercedes vehicle uses a self-regenerating catalyzed ceramic particulate trap located before the turbocharger. If a self-regenerating light-duty system could be successfully adapted to a heavy-duty diesel bus application, then the heavy-duty system would be demonstrated in California in regular transit service.

The term "regeneration" is used to describe the oxidation or burning of particulate accumulations trapped or filtered from the diesel exhaust by the ceramic filter substrate. Regeneration normally requires temperatures between 510 to 610°C. "Self-regeneration" implies that the process of cleaning is not directly assisted by using external means to add heat, and that the regeneration occurs spontaneously rather than in response to programmed conditions. After regeneration is initiated, exothermic reactions take place that can cause high temperatures to occur in the substrate.

In this program, a unique ceramic trap assembly was designed for application to a GMC RTS II 04 transit bus supplied to the project by the Southern California Rapid Transit District (SCRTD) on behalf of the ARB. Four complete ceramic trap units were evaluated to varying degrees. The first trap, Trap No. 1, utilized Corning ceramic honeycomb filter material (EX-47 substrate) without a catalyst coating. It was installed behind the rear seat of the bus as a muffler replacement to determine the feasibility of the trap design. Exhaust piping was fabricated to allow experimentation with the candidate trap units at two points in the exhaust stream, either <u>before</u> or <u>after</u> the turbocharger. The ceramic trap design proved to be of adequate size to allow reasonable times between regenerations. Trapping efficiency was good, such that no visible smoke (≤5 percent opacity) was emitted during experimentation, and measured particulate was reduced by more than 70 percent. Regeneration of the first unit was accomplished using an acetylene torch to achieve exhaust gas temperatures of 550°C. After proving the design concept used to build Trap No. 1, three additional ceramic trap units with different proprietary catalyst coatings were fabricated.

*Superscript numbers in parentheses refer to references at the end of this report.

Trap No. 2 was built utilizing Corning EX-66 substrates and a proprietary catalyst coating, "A", similar to that used on the Mercedes diesel car. Emission results with this unit showed good reduction of HC and CO, along with an average 90 percent reduction of particulates. Virtually no visible smoke was observed from the bus when this unit was used. Very faint smoke was noted during snap-idle operation (a rapid increase in engine speed from curb-idle speed to high-idle speed), and then only when the trap was in a relatively clean state. This second trap unit was regenerated using engine upset to increase the exhaust temperature. Engine upset consisted of altering the engine air-to-fuel ratio by venting a portion of the air box pressure used to scavenge the 2-stroke engine. Noticeable regeneration took place when the trap substrate temperatures reached approximately 510 to 550°C. Unfortunately, this trap was damaged during road course experimentation.

Trap No. 3 consisted of Corning EX-54 substrates coated with a different catalyst formulation, "B." This unit did not reduce HC and CO emissions, but did provide greater than 80 percent reduction in total particulate emissions. No visible smoke was noted with this trap, whether located after or before the turbocharger. The engine had to be upset and the engine load brought to substantial levels to create the high exhaust temperature needed to obtain a regeneration. Noticeable regeneration took place when the trap substrate temperatures reached 510 to 550°C. The maximum substrate temperature noted during test work with Trap No. 3 was 830°C. Damage to the substrate can occur near 1000°C.

Trap No. 4 was fabricated using EX-47 ceramic substrates catalyzed with formulation "C." The catalyzed EX-47 material was expected to be more durable than either Trap No. 2 or 3 and has a smaller pore size. This fourth trap assembly reduced particulate emissions on the bus cycle by about 90 percent. No visible smoke was noted during any portion of the chassis dynamometer test work with the unit positioned before the turbocharger. As with the other two catalyzed traps, regeneration required substrate temperatures between 510 and 550°C (almost the same as the first uncatalyzed trap). Because results were similar to those obtained with Trap Nos. 2 and 3, test work on Trap No. 4 was limited.

Particulate, HC, CO, and NO_x emissions from the bus, with and without the various particulate traps, are summarized in Table 1. Smoke levels noted over a variety of engine exercises are summarized in Table 2. In addition, acceleration performance times for the bus, with and without the traps, are summarized in Table 3.

Plans to fit the bus with the best trap/regeneration system for demonstration purposes required the selection of a first choice. The criteria for selection of first choice were:

1. ≥70% reduction in total particulate
2. no visible smoke (≤ 5 percent opacity)
3. lowest regeneration temperature
4. least effect on engine performance
5. best reduction of CO and HC emissions

TABLE 1. SUMMARY OF EMISSIONS OF BUS 8296 WITH AND WITHOUT PARTICULATE TRAPS ON THE CHASSIS BUS CYCLE

Bus Configuration	Emissions, g/km				Fuel Usage	
	HC	CO	NO_x	Part.	kg	km/kg
Average Baseline	1.55	5.96	12.05	1.63	2.58	1.80
Without Muffler	1.5	4.3	11	1.6	2.5	1.9
Trap No. 1 Before Turbo	2.5	9.5	11	0.3	2.3	2.0
Trap No. 1 After Turbo	1.7	7.0	10	0.3	2.4	2.0
Without Muffler	2.0	9.2	12	2.4	3.0	1.6
Trap No. 2 Before Turbo	0.6	1.8	13	0.2	3.0	1.6
Trap No. 2 After Turbo	0.4	4.8	13	0.1	3.0	1.6
Without Muffler	2.1	8.4	12	2.1	2.5	1.9
Trap No. 3 Before Turbo	1.4	19	10	0.3	2.6	1.8
Trap No. 3 After Turbo	1.6	11	11	0.3	2.7	1.7
Without Muffler	2.0	12	13	2.9	3.0	1.6
Trap No. 4 Before Turbo	1.9	26	12	0.2	3.0	1.6

TABLE 2. SUMMARY OF SMOKE OPACITY LEVELS OF BUS 8296 WITH AND WITHOUT PARTICULATE TRAPS

	Smoke Opacity, %			
	Idle[a]	Snap Idle	Stall	Acceleration[b]
Baseline	0.8	35	4.2	29-37
Without Muffler	0.4	27	2.1	20-28
Trap No. 1 Before Turbo	0.3	2.0	1.2	1.2
Trap No. 1 After Turbo	0.3	2.0	2.3	0.5
Without Muffler	0.4	37	4.2	25-30
Trap No. 2 Before Turbo	0.3	1.5	0.6	2.0
Trap No. 2 After Turbo	0.3	1.0	0.3	1.0
Without Muffler	0.5	48	6.3	32-44
Trap No. 3 Before Turbo	0.2	1.0	1.4	1.5
Trap No. 3 After Turbo	0.1	0.5	0.5	0.5
Without Muffler	0.8	48	9.0	43-50
Trap No. 4 Before Turbo	0.1	1.2	2.3	2.3

[a]idle in neutral
[b]peak measured during CBD cycle

TABLE 3. SUMMARY OF ACCELERATION TIMES OF BUS 8296 WITH AND WITHOUT PARTICULATE TRAPS

Speed Range, mph	Acceleration Time, second			
	0-10	0-20	0-40	0-50
Baseline	4.8	10.5	31.3	50
Without Muffler	4.3	9.8	33	54
Trap No. 1 Before Turbo	4.3	10.4	33	52
Trap No. 1 After Turbo	4.5	10.2	31	48
Without Muffler	4.0	9.5	29	48
Trap No. 2 Before Turbo	4.3	9.8	31	49
Trap No. 2 After Turbo	4.7	10.3	31	50
Without Muffler	4.4	9.4	29	46
Trap No. 3 Before Turbo	4.4	10.5	35	57
Trap No. 3 After Turbo	4.1	9.6	31	52
Without Muffler	4.3	9.5	29	48
Trap No. 4 Before Turbo	4.3	10.2	33	54

All three catalyzed traps were essentially equivalent based on the first four criteria listed above. Only Trap No. 2 had the distinction of reducing CO and HC emissions. The most critical item, relative to pursuing a field demonstration, was criterion No. 3. No low temperature regenerations were noted for any of the three catalyzed ceramic units evaluated in the program.

The high exhaust temperatures required for regeneration (510 to 550°C) could be obtained with high engine loads or with engine upset in some cases. Because the catalyzed traps evaluated in this program lacked suitable low-temperature regeneration characteristics to permit general use of the bus in an in-service environment, a field demonstration was discouraged. Based on the information and alternatives presented, further work with catalyzed ceramic traps developed for this program was terminated at the request of the ARB. The remaining effort, reserved for demonstration purposes, was redirected by the ARB to examine the impact of low-sulfur and low-aromatic diesel fuel on heavy-duty diesel emissions (to be reported in Volume II). The bus was restored to its original configuration and returned to SCRTD, October 23, 1986.

II. BACKGROUND AND SCOPE OF THE PROGRAM

Heavy-duty diesel vehicles are a major contributor to NO_x and particulate matter air pollution. California's most severe air pollution problems occur in the South Coast Air Basin (Los Angeles area), where heavy-duty diesel vehicles are estimated to account for 23 percent of total on-road vehicle NO_x emissions and 55 percent of total exhaust particulate emissions.(1) Without further controls, these percentages are predicted to increase by the year 2000(1) to 36 percent of NO_x and 87 percent of particulates. In addition, visibility is predicted to further degrade in California due to the increased number of heavy-duty diesels.(1) Bus emissions are of particular concern; because buses are typically operated exclusively in urban areas; over the busiest roadway corridors with highest population exposure; and with exhaust typically discharged at ground level, directly into the human breathing zone.(3)

The objective of the work reported here was to equip a transit bus with a particulate trap system that eliminates "visible smoke," reduces exhaust particulates by 70 percent, and is self-regenerating or automatic. If the self-regenerating particulate trap concept could be developed, then a bus with this emission control system installed would undergo transit service to demonstrate durability for one year.

In accord with the desires of the California Air Resources Board (ARB) to adapt current light-duty diesel particulate control technology, this work involved the application of a trap/regeneration system similar to that currently used on the diesel Mercedes-Benz automobiles sold in California. Another supposedly workable light-duty particulate control system, reported by Volkswagen, used a fuel additive containing manganese. In ARB Mail-Out 85-49 on January 16, 1985, use of manganese in trap-equipped diesel vehicles was discouraged. Therefore, evaluations involving manganese fuel additives, as well as other potential fuel additives, were excluded from this work.

The Mercedes-Benz diesel particulate control system consists of a ceramic honeycomb filter placed in the exhaust stream to filter out, or trap, the particulate as it is exhausted from the engine. The ceramic filter has been coated with a catalyst to assist in the cleaning of accumulations "trapped" on the surface of the exhaust gas filter. Periodic or continuous cleaning of accumulations (regeneration) on the filter are necessary to prevent plugging the filter and consequently raising the engine exhaust backpressure beyond engine design limits. High temperatures, near 600°C (1112°F), are typically needed to clean these accumulations; however, it is claimed that use of proprietary catalyst coatings can promote the cleaning of accumulations at lower temperatures approaching 400°C (750°F). Cleaning of the accumulation from the filter at lower temperatures is advantageous because exhaust gases may often reach (or can easily be made to reach) these lower temperature ranges during normal vehicle operation, resulting in a periodic or continuous regeneration of the trap. To favor continuous regeneration, the catalyzed ceramic trap used on the Mercedes-Benz light-duty diesel vehicle is located between the engine exhaust manifold and the exhaust inlet to the turbocharger. Positioning the trap "before" the turbocharger takes advantage of higher-temperature exhaust gases than those present "after" the turbocharger.

In addition, some specific tuning of the engine can be used to further increase exhaust gas temperatures, favoring frequent trap regeneration.

The technical approach used in this work was to obtain a complete transit coach for application of a catalyzed ceramic trap. The bus chosen was one produced by General Motors and powered by a Detroit Diesel Allison Division (DDAD) 6V92TAC engine. This bus represents a large population of buses on the road in California as well as other parts of the country. The engine uses a two-stroke cycle, which causes the exhaust to be considerably cooler than that from a four-stroke cycle engine. In addition, the two-stroke engine exhaust typically contains more organic (oily or unburned fuel-like) constituents than noted for four-stroke engines.

Positioning the catalyzed ceramic trap assembly before the turbocharger in a heavy-duty application was expected to decrease the effectiveness of the turbocharger; and thereby cause a detrimental effect on engine performance. Consequently, provisions for experimentation with the trap located both after the turbocharger and before the turbocharger were included in this work. In the event that exhaust temperatures of the two-stroke bus engine were not found sufficient to cause the trap to be cleaned or self-regenerated within the typical bus operating envelope, experiments were planned to increase the exhaust temperature. Two basic approaches used in this work to promote trap regeneration were: (1) altering the engine air-to-fuel ratio; and (2) utilizing the trap catalyst to oxidize a light hydrocarbon, such as methanol, to increase trap temperatures.

Judging the effectiveness of applying a catalyzed ceramic trap to a bus required measurement of both regulated and unregulated emissions from the bus, operated on a chassis dynamometer with and without the trap. Use of the chassis dynamometer allowed experiments to assess the usefulness of the three catalyst formulations evaluated during this work. In addition, use of the chassis dynamometer allowed comparative experimentation on methods to promote trap regeneration.

A goal of the program was to fit the bus with a trap suitable for over-the-road demonstration in California. The experimental work described here included some preliminary road evaluations to address the acceptability of the system evolving from this program for continued demonstration in public view in Southern California.

An overview of the intended scope of the program is given in Table 4. The program incorporated obtaining a bus from SCRTD; determining the baseline emissions of the bus; and evaluating the trap container, the ceramic substrate, and the overall trap design for structural integrity and emission performance. In addition, methods to increase exhaust gas temperature to favor regeneration were evaluated.

An uncatalyzed trap assembly was used to establish techniques for construction, piping, and initial placement of the trap assembly in the bus. Some experiments to investigate the effect of the trap on exhaust pressure drop and turbocharger performance were conducted with this first trap. Regeneration of the uncatalyzed trap was accomplished by placement of a manually-controlled burner (acetylene torch) in the exhaust stream.

TABLE 4. OVERVIEW OF THE INTENDED PROGRAM FOR PARTICULATE TRAP DEMONSTRATION

Receive Bus

Refuel on Low-Sulfur Fuel

Establish Baseline Emissions and Performance

Fit Trap Assembly No. 1

Evaluate Performance

Investigate Methods of Altering Exhaust Gas Properties

Evaluate Trap No. 2, Catalyst Formulation "A"

Evaluate Trap No. 3, Catalyst Formulation "B"

Evaluate Trap No. 4, Catalyst Formulation "C"

Review Results and Decide on Best Choice

Fit Best Choice

Establish Detailed Emission Characterization and Performance With Trap

Transport Bus

Demonstrate

After these initial experiments, three trap assemblies with different catalytic coatings were constructed for evaluation. The highest priority was given to evaluating the catalyzed trap modeled after the Mercedes-Benz automotive application. All three catalyzed units were tested for a short time to evaluate which catalyst formulation was the most applicable to the bus.

Based on the results of those experiments, a best choice trap/regeneration system was to be chosen. Efforts to make the catalyzed trap/regeneration system function over all modes of typical bus operation, without adding heat by auxiliary methods or including relatively high-load engine operation along with engine upset were unsuccessful. Based on the proposed options for establishing a field demonstration in California, the ARB decided to stop working toward demonstration of hardware developed in this program. The bus was restored to the as-received configuration, and then returned to SCRTD.

III. DESCRIPTION OF TEST PROCEDURES, TEST FUEL, BUS, AND TRAP DESIGN USED IN THIS PROGRAM

The intent of this program was to adapt a light-duty diesel particulate control system to a heavy-duty diesel vehicle. The objective was to eliminate visible smoke and to reduce measured particulate emission 70 percent, by applying a catalyzed ceramic trap to a transit. This section of the report describes the bus, along with the properties of the low sulfur fuel used. It also describes the trap design developed for the program and used in the fabrication of the four trap units evaluated. Procedures for chassis dynamometer testing, road testing, noise measurements, performance measurements, and emission characterization also are described in this section.

A. The Test Vehicle and Fuel

The bus selected for use in this program was to be in road worthy condition and have as near average fuel and oil consumption as possible. The bus was to have average smoke emissions, that is, its engine was not to be in the failed or malfunctioning mode. The bus supplied to SwRI by Southern California Rapid Transit District (SCRTD), on behalf of the California Air Resources Board, was a 1980 GMC RTS II 04 transit coach, 40 feet in length.

Bus No. 8296, shown in Figure 1, was selected by SCRTD for use in this program. This vehicle had accumulated approximately 100,000 miles on a 1980 DDAD 6V-92TAC engine/power-pack installed in the bus chassis in 1983. The bus was selected on the basis of manufacturer, model, engine type, mileage, fuel economy, and oil consumption. The bus was taken from service and evaluated for performance and smoke on a chassis dynamometer at SCRTD. During that evaluation, it was apparent that full power performance was poor.

Injector timing was checked and set to manufacturer's specifications (1.460 in.), and throttle delay was checked and set (0.636 inches). Chassis dynamometer testing of the bus still indicated low power. The problem was discovered to be a defective treadle assembly, which was not allowing the throttle to go to full power position. After this "tune-up," engine performance was satisfactory. Other scheduled maintenance in support of the chassis was conducted by SCRTD.

After these repairs and adjustments were completed, the bus was approved for delivery to SwRI for use in the project. The bus was fitted with highway-grade tires to facilitate reliable transport from California to Texas. A "certificate of insurance" was issued to SCRTD on behalf of SwRI to provide the necessary insurance coverage. An arrangement between SwRI and SCRTD was signed, and SwRI took delivery of the bus in California on September 11, 1985.

There was some concern that this "tuned" bus may not represent the California smoke, or particulate, problem to be addressed during this trap demonstration project. The ARB approved the use of this bus for this program, but requested that preliminary emissions data be collected on the bus "as-

FIGURE 1. GMC RTS II TYPE 04 TRANSIT BUS SUPPLIED TO THE PROGRAM BY SCRTD

received" by SwRI. These data were requested for comparison to other SwRI data and information gathered separately by ARB, SCRTD, and others. If "as-received" smoke emissions were low by comparison to other data, then adjustments could be made to generate smoke emissions typical of levels observed in the field.

No problems were encountered during transport, and the bus was available to the Department of Emissions Research on September 16, 1985. The bus fuel system was purged and filled with low sulfur test fuel. The bus was then operated over a straightaway to conduct some preliminary observations of smoke and performance. As reported by SCRTD, the observed smoke during accelerations was almost imperceptible. In addition, the time for engine speed to reach stall rpm seemed excessive.

The properties of the low-sulfur No. 2 diesel fuel used in this program, designated as EM-619-F, are given in Table 5 along with properties of typical No. 2 diesel emissions test fuel (EM-597-F) for comparison purposes. Both of these fuels were used previously in the evaluation of the Johnson Matthey traps for the ARB. The low-sulfur fuel contained 0.05 weight percent sulfur, compared to the typical No. 2 emissions fuel which contained 0.35 weight percent sulfur. The lower initial boiling (IBP) to 30 percent boiling points of the low sulfur fuel resemble those typically associated with a No. 1 diesel fuel. All evaluations were conducted on this low-sulfur test fuel.

The bus was weighed, and a chassis dynamometer inertia of 31,000 lb was selected to simulate a passenger load of about 22 persons. Preliminary emissions and performance data were obtained for the bus in the as-received condition using chassis test procedures. Based on these preliminary emissions results, the ARB decided that the bus was not "smokey" enough to make meaningful evaluations of the ceramic trap media. On this basis, the ARB directed that the injection timing be retarded from 1.460 to 1.470 in. and that the throttle delay be shortened from 0.636 to 0.504 inches. The prescribed adjustments were made to the engine, and preliminary emissions testing was continued. Based on the higher smoke opacities obtained after adjustment of the engine, approval to proceed with the detailed baseline emissions characterization was given.

Upon arrival of the bus, a preliminary trap design was developed further considering space limitations and project objectives. It was decided that the only space adequate for placement of a trap in the engine compartment, without causing engine maintenance problems, was that occupied by the existing muffler. Figure 2 shows the engine compartment of the GMC RTS II bus as viewed from the rear of the bus. Figure 3 shows the upper portion of the engine and the front exhaust manifold, viewed through the inspection hatches located behind and under the rear seat. Figure 4 shows the top of the muffler, as viewed through the inspection hatch located under the rear seat.

B. Trap Design

Based on the bus selected bus and the resulting constraints on space available for placement of a ceramic trap assembly, the existing muffler location was chosen. In addition, using the existing muffler location allowed

TABLE 5. PROPERTIES OF BASELINE AND LOW SULFUR FUELS

Description	DF-2	Low Sulfur
Code	EM-597-F	EM-619-F
Density, g/m	0.8488	0.8473
API Gravity. 60F	35.2	35.5
Sulfur, wt. %	0.35	0.05
Viscosity, at 40°C, cS	2.5	2.4
Flashpoint	162	142
Distillation, °F		
IBP	375	339
10	431	394
20	451	421
30	469	445
40	487	467
50	505	487
60	523	509
70	543	531
80	567	560
90	598	598
EP	653	650
Cetane Number	46.2	45 (cal.)
Composition, Vol %		
Aromatics	32.1	36.2
Olefins	1.3	--
Saturates	66.6	63.8
Carbon, wt. %	86.12	86.53
Hydrogen, wt. %	12.92	13.06
H/C Ratio	1.79	1.80

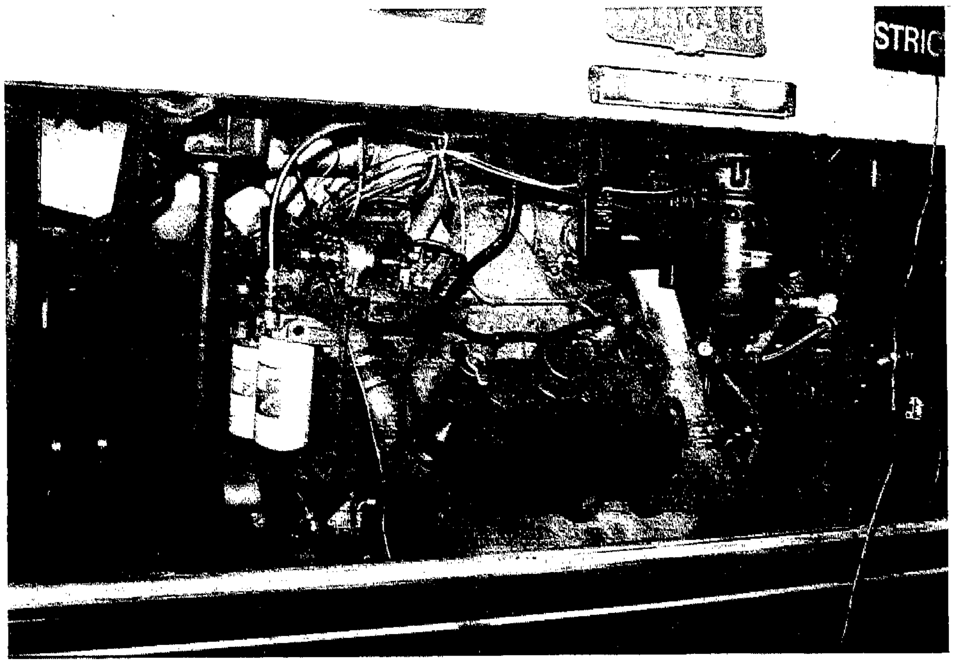

FIGURE 2. ENGINE COMPARTMENT OF BUS 8296
IN "AS-RECEIVED" CONFIGURATION

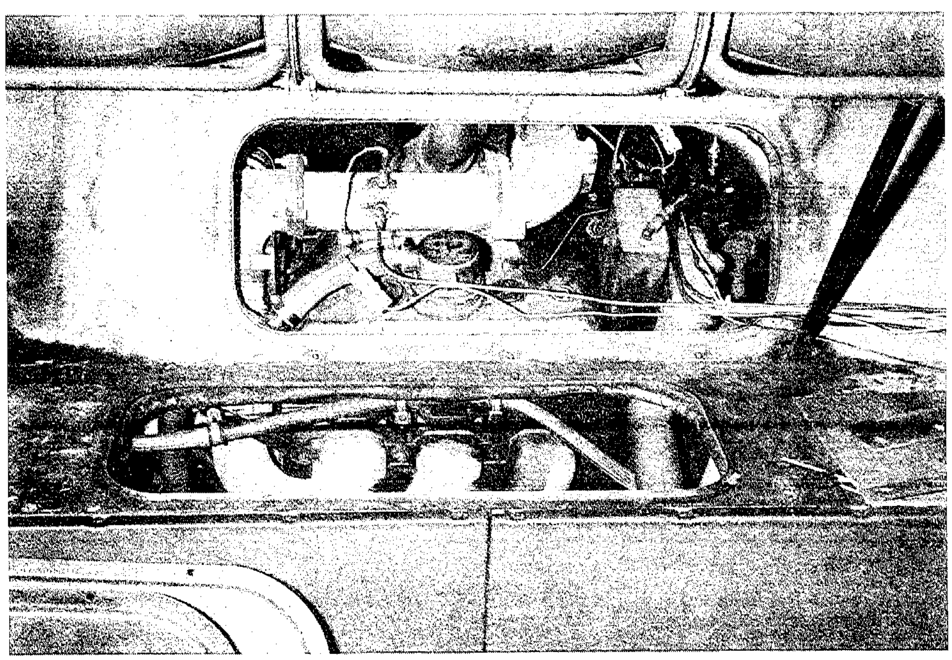

FIGURE 3. VIEW OF ENGINE COMPARTMENT THROUGH THE TWO
INSPECTION PORTS PROVIDED UNDER THE REAR SEAT

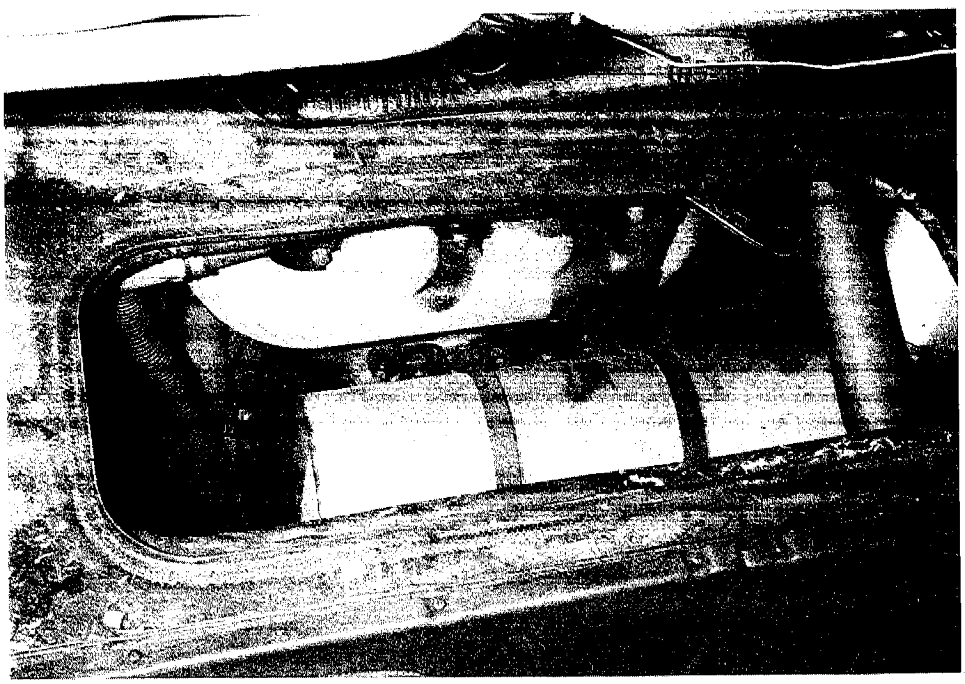

FIGURE 4. VIEW OF MUFFLER THROUGH INSPECTION PORT LOCATED UNDER REAR SEAT OF BUS

experimentation with trap placement before and after the turbocharger by rerouting exhaust gases. Representatives of Corning Glass Works were contacted, and design considerations concerning the application of corderite ceramic material were discussed. Several geometric options for the finished ceramic filter pieces were considered in conjunction with space limitations, research flexibility, and the conditions to which the trap would be subjected. A preliminary trap design was established by SwRI on August 9, 1985, on the basis of projected exhaust flows, material availability, and space limitations for the application of a ceramic filter within the engine compartment of the bus. The basic concept was modified to the design sketched as Figure 5.

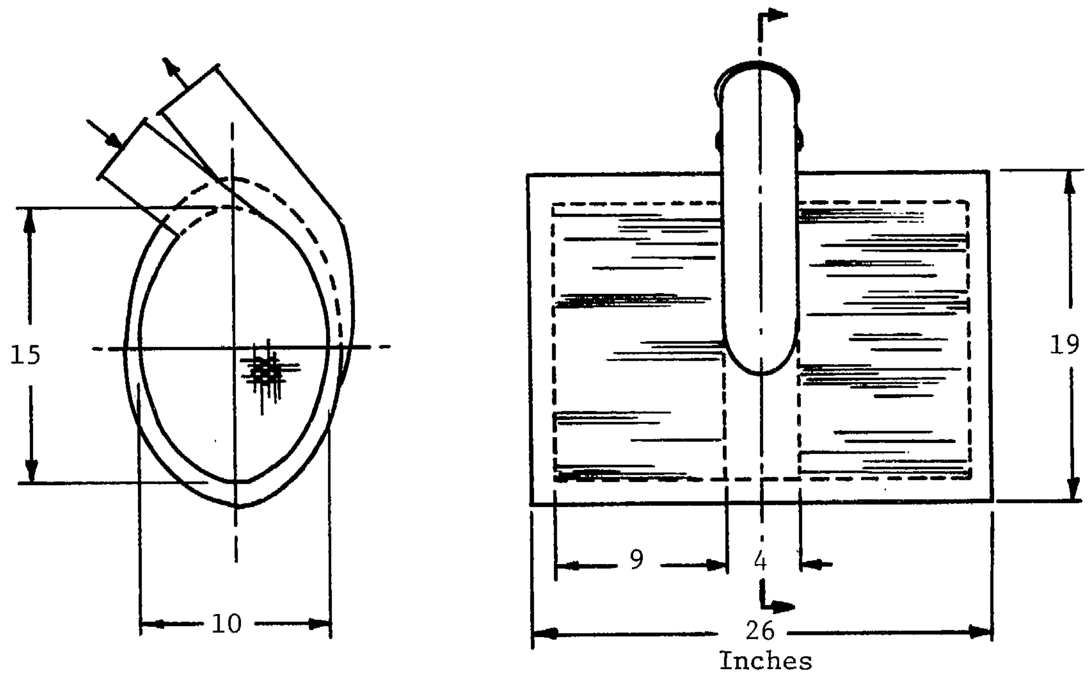

FIGURE 5. PRELIMINARY TRAP DESIGN FOR THE GMC RTS II 04 BUS

The design allowed the exhaust gases to enter a common plenum, between the two pieces of ceramic trap substrate, held in place by a common container. The exhaust gases passed through the ceramic substrates, to a common outer container, and around, to the outlet. The inlet and outlet of the trap assembly were planned so that the exhaust piping could be changed to accommodate experimentation with the trap in the before and after turbocharger positions without actually relocating the trap assembly. The outer container was designed to contain exhaust gas pressures near 21 psig, typically experienced when the exhaust flow was routed so that the trap was before the turbocharger. The design concept of using a container within another container saved space, and reduced heat and pressure differentials between the ceramic substrates of the trap assembly and the outside surface of the assembly.

After receiving the bus, measurements around the exhaust muffler were confirmed, and the initial trap design was accordingly modified. The cross sections of the ceramic substrates were changed to 15 x 10 in. ellipses, and they had a length of 9.0 inches. Templates of the desired cross section were distributed to Corning Glass Works and Arvin Automotive for fabrication of the ceramic filter substrates and for "canning," respectively. "Canning" is the mounting of the fragile ceramic substrate into a stainless steel sheet metal container with insulation, to maintain slight compressive stress on the ceramic substrate.

The outer container of the trap was fabricated from 16 gage mild steel. The outer container measured 27 3/8 in. long, with an elliptical cross-section shape of 13 in. by 17 inches. The outer container was sealed and pressure-tested to 30 psig. Some desirable distortion of the side panels occurred, but no other significant deformation occurred.

Two ceramic substrate sections made of Corning EX-47, and canned by Arvin Automotive, were received November 12, 1985. Each substrate assembly, as shown in Figure 6, weighed about 35 pounds. The cans of the two uncatalyzed ceramic substrates were welded together with a five-inch spacing between the faces of the ceramic substrates. Then this ceramic filter assembly was positioned inside the outer container so that there was approximately a 3/4 in. air space between the surface of the ceramic filter assembly and the outer container. Appropriate tubing connections were completed. A cross section of a trap is shown in Figure 7 to illustrate the inlet and outlet piping arrangements. The ceramic filter assembly was essentially suspended inside the outer container by four support bolts located in the center of the five-inch spacing between the two substrate faces. Borescope inspection ports were incorporated so that they could be used for obtaining pressure and temperature data during trap operation. The completed assembly, shown in Figure 8, was designated as Trap No. 1.

After road work and emissions testing of the bus was completed in its baseline configuration, the muffler of the bus was removed. Trap No. 1 was positioned in the space normally used for the muffler. New support straps were used in conjunction with existing brackets to secure the trap assembly. Exhaust piping was routed to and from the trap assembly, so that experiments could be performed with the trap <u>before</u> the turbocharger, <u>after</u> the turbocharger, or with exhaust gases routed around the trap. acetylene torch was used to regenerate the uncatalyzed trap assembly.

It should be recognized that the "Mercedes system" includes not only the catalyzed ceramic trap assembly, but also the car, the engine, and the operating envelope of the vehicle itself. It was recognized by both SwRI and catalyst suppliers that <u>rote</u> transfer of the "Mercedes system" to a bus was not feasible. Catalyst companies agreed to submit catalyst coatings on the basis of simulating the approach used in the "Mercedes system," while considering the unique characteristics of the bus, the engine, and its particular operating envelope.

The use of several porosities of Corning corderite diesel exhaust filter material was suggested on the basis of filter efficiency, back pressure characteristics, and potential interaction with various catalyst coatings. The EX-47 material typically has particulate trapping efficiency near 90 percent.

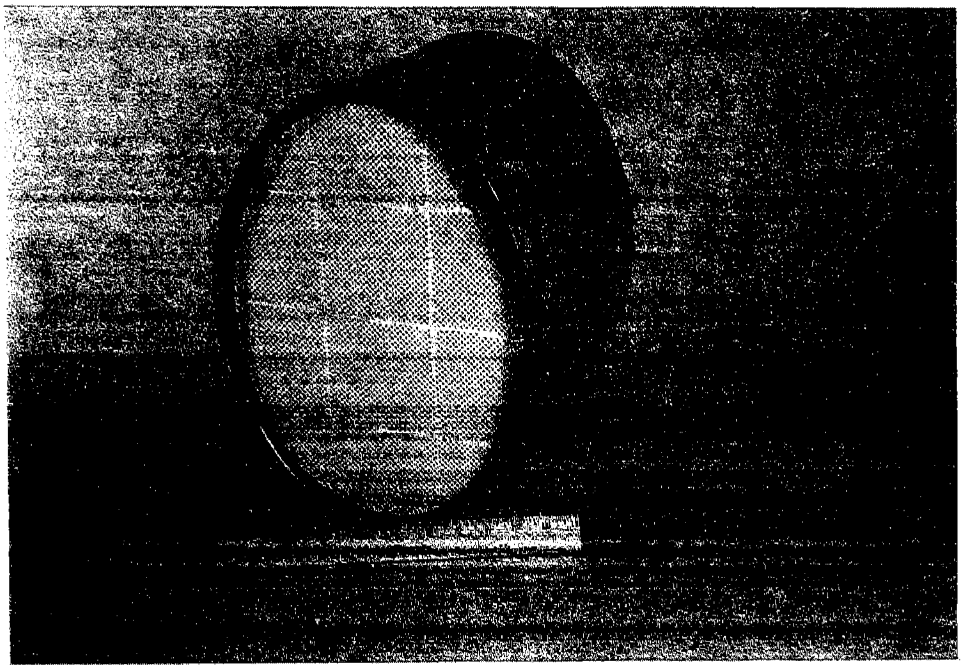

FIGURE 6. ONE OF TWO CERAMIC SUBSTRATE ELEMENTS USED TO MAKE A PARTICULATE TRAP ASSEMBLY

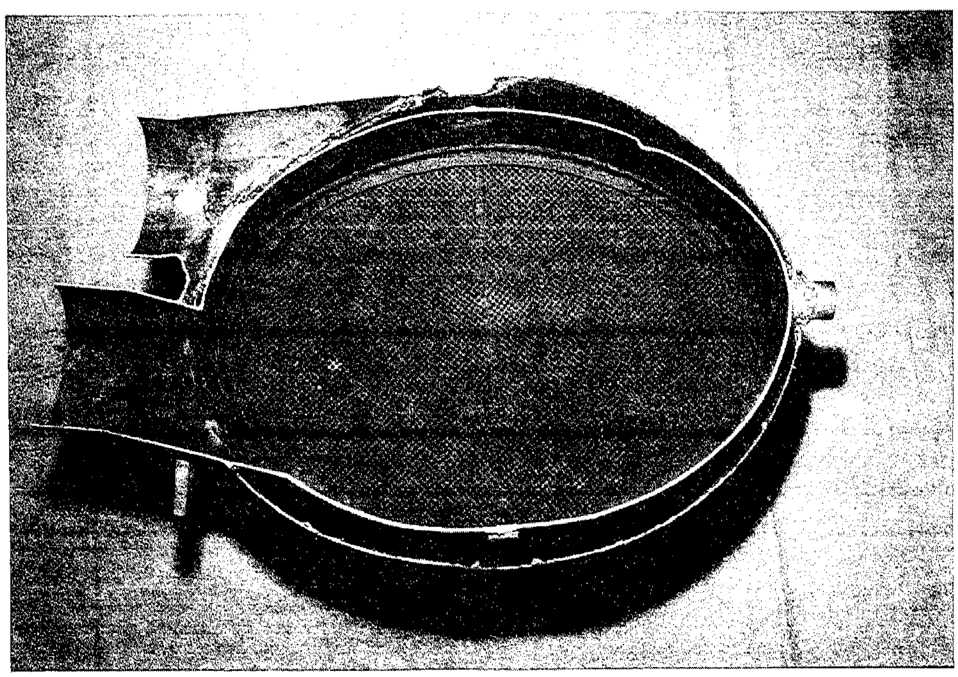

FIGURE 7. CROSS SECTION OF TRAP ASSEMBLY SHOWING THE INLET AND OUTLET FLOW PATHS

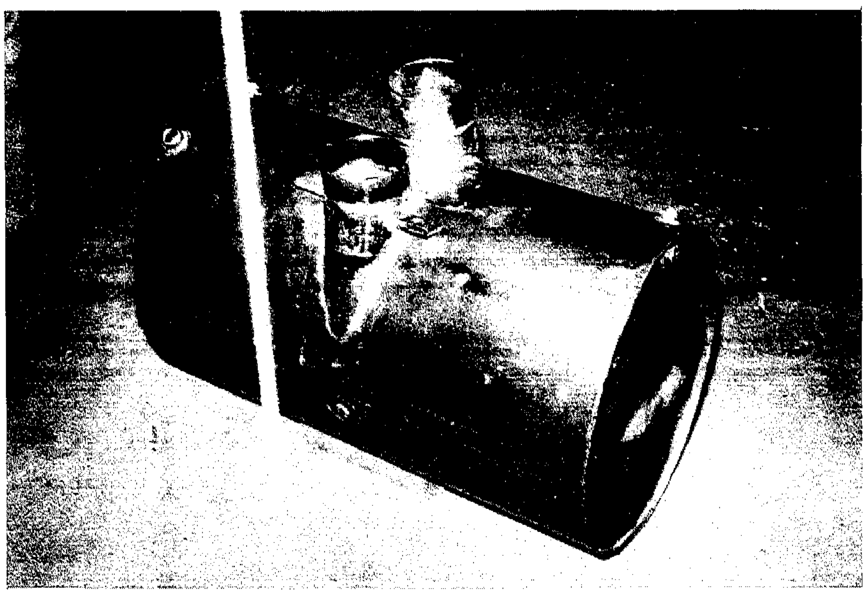

FIGURE 8. COMPLETED TRAP ASSEMBLY READY FOR FITTING AS A MUFFLER REPLACEMENT UNDER THE REAR SEAT

The EX-66 exhibits a range of efficiency from 25 to 68 percent (below the 70 percent target for this program). Although it was expected that the catalyzed EX-66 unit would perform in excess of 70 percent efficiency, a more efficient unit made of EX-54 also was ordered for evaluation. The EX-54 material exhibits efficiencies that range from 65 to 80 percent.

Two EX-66 ceramic filter substrates were catalyzed with formula "A," and were received February 18, 1986. These catalyzed substrates were built into Trap No. 2, almost identical to Trap No. 1. The outer container weldment was modified slightly to reduce pressure drop of exhaust gases leaving the ceramic filter assembly of the trap. Two EX-54 ceramic filter substrates, catalyzed with formula "B," were received June 3, 1986, and were built into Trap No. 3. The two EX-47 ceramic filter substrates, originally built and tested in Trap No. 1, were removed and later catalyzed with formula "C." These two catalyzed EX-47 ceramic substrates were received in June 6, 1986 and were built into Trap No. 4. Table 6 lists the trap assemblies tested in this program.

TABLE 6. LIST OF TRAP ASSEMBLIES TESTED IN THIS PROGRAM

Trap No.	Substrate	Catalyst
1	EX-47	none
2	EX-66	"A"
3	EX-54	"B"
4	EX-47	"C"

When the initial trap assembly was positioned in the engine compartment of the bus, the exhaust inlet section of the turbocharger housing was reoriented. Exhaust tubing (four-inch diameter) was routed from the exhaust pipe "Y", which combines exhaust gas from both manifolds, through the trap and to the exhaust side of the turbocharger for testing the before turbocharger position of the trap. This insulated piping arrangement is shown in Figure 9. The plain pipe was used to route exhaust from the turbocharger, and to the back of the bus. A "before turbocharger bypass pipe" was fabricated so that the trap could be easily isolated from the exhaust stream. This pipe is shown in the upper portion of Figure 10, and is covered with white insulation. It connects the "Y" to the turbocharger. With this pipe in place, along with the plain pipe shown in Figure 9, evaluations "without muffler" could be conducted. Figure 10 shows the after turbocharger piping arrangement, using an insulated pipe routed from the turbocharger to the trap, and a "U"-shaped insulated pipe to route the exhaust from the trap, down and out, behind the bus. Existing exhaust manifolds and piping leading to the turbocharger were insulated with a formable ceramic felt to retain as much exhaust heat as possible.

C. Test Procedures

The bus used in this program was tested on the heavy-duty chassis dynamometer for comparison of emissions and acceleration performance, and to study trap regeneration scenarios. The bus was also tested on a straight,

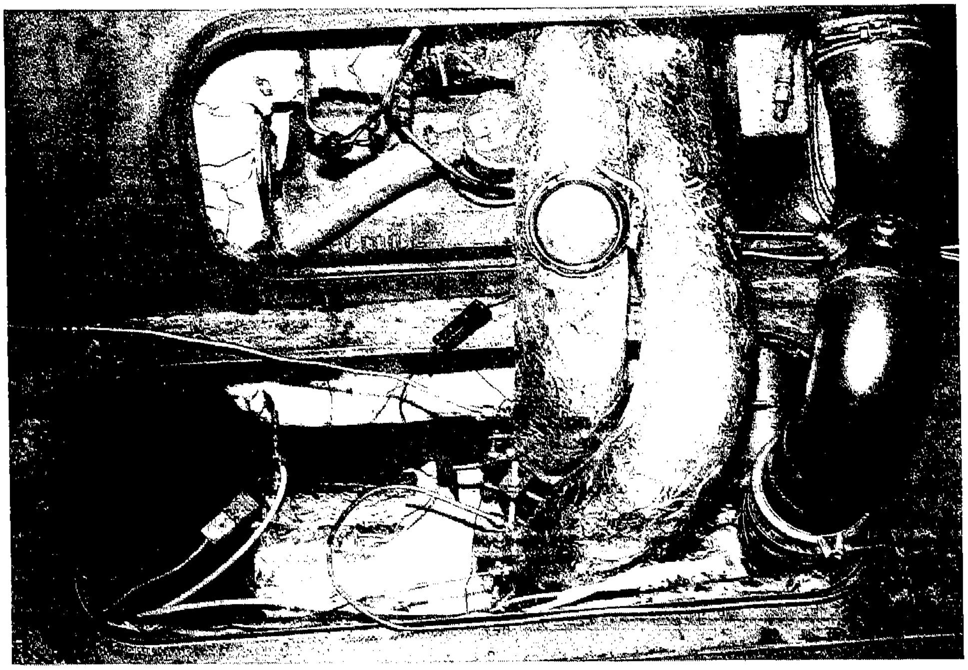

FIGURE 9. INSULATED PIPING ARRANGEMENT USED TO "POSITION" THE TRAP BEFORE THE TURBOCHARGER

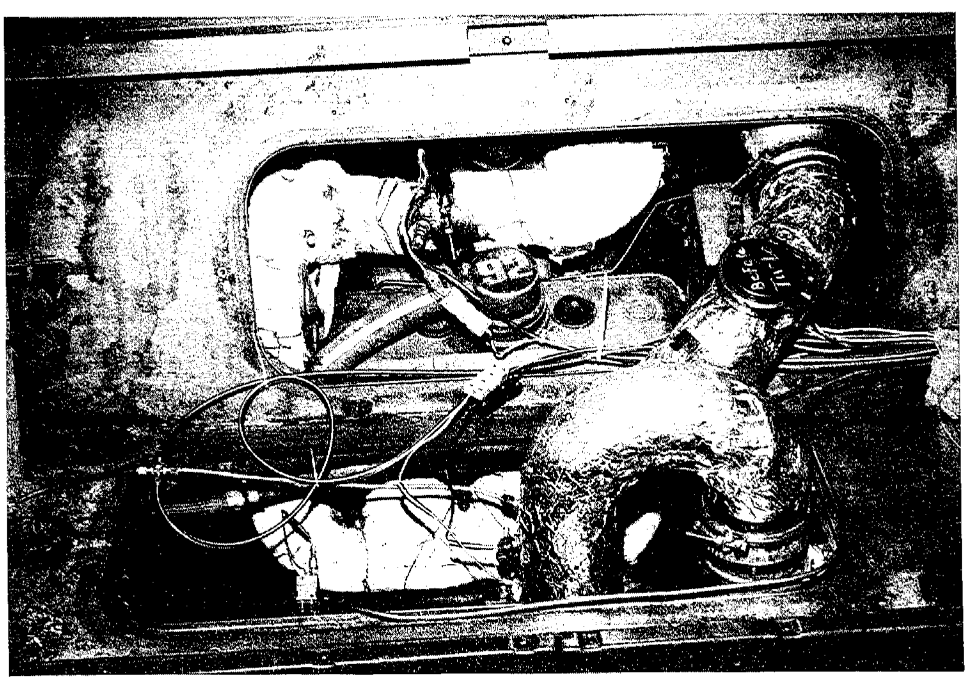

FIGURE 10. INSULATED PIPING ARRANGEMENT USED TO "POSITION" THE TRAP AFTER THE TURBOCHARGER

short track for comparison of noise level; and was operated over a defined road route to obtain bus performance along with temperature and pressure data. These data were obtained on runs made under baseline conditions, conditions with various trap units fitted in different positions, and during various regeneration scenarios.

1. Chassis Dynamometer

The chassis testing in this program was based on the test procedure outlined in the EPA "Recommended Practice for Determining Exhaust Emissions From Heavy-Duty Vehicles Under Transient Conditions."[4] The chassis dynamometer used was a tandem-axle Clayton heavy-duty unit modified by the addition of eddy-current power absorbers and inertia wheels. Electronic programming of the system enables the use of almost any required speed-power curve. By utilizing an electrical signal from the vehicle braking system, electrical braking of the dynamometer rolls is also provided. Each of the absorption units in tandem has dual rolls that are 8.625 inches in diameter. Inertia simulation is provided by an appropriate combination of directly coupled inertia wheels. Maximum inertia simulations readily attainable are 49,000 lb for single-drive-axle vehicles and 76,000 lb for tandem-drive-axle vehicles. Using the programmable chassis dynamometer, the procedure developed for road load simulation of a vehicle involves establishing the speed-power curve, determining inertia simulation, and determining system friction.

The equation selected for calculation of the speed-power curve used for evaluations on the chassis dynamometer is as follows:

$$RLP = F \times 0.67(H - 0.75)\ W \times (V/50)^3 + 0.00125 \times LVW \times V/50$$

Where:
RLP = Road load power, horsepower
F = 1.00 for tractor-trailer and 0.85 for city bus
H = Average maximum height, feet
W = Average maximum width, feet
LVW = Loaded vehicle weight, pounds
V = Velocity, mph

The equations used for determination of dynamometer torque and load are as follows:

Dynamometer Torque, ft-lb = Power, hp x 134.8/Velocity, mph
Dynamometer Load, lb = Torque x 12/Load Arm, inches

These equations were developed in conjunction with experimental data obtained with trucks and buses and reported in reference.[5]

When the appropriate inertia wheels were fitted to the dynamometer to simulate 31,000 lb, the bus was positioned on the rolls. The rear axle vertical loading was reduced by blocking up the frame of the bus, and cooling fans were positioned to reduce the risk of tire damage. With the bus in position, bus exhaust-to-CVS piping was installed.

With vehicle installation complete, the total system absorbed horsepower was determined using coastdowns. This was accomplished by obtaining repeatable 88 to 8 kph coastdown speed-versus-time data, and then solving for the instantaneous decelerations. From the instantaneous decelerations, the power absorption of the vehicle-dynamometer system was determined as a function of vehicle speed. The speed-power curve for programming into the dynamometer controller was then determined by difference between the total power required on the road (based on previous documentation [5]) and the power absorbed by the vehicle-dynamometer system.

The bus was set on the chassis dynamometer with a simulation of 31,000 lb inertia. Total road load for the bus was 79 hp at 50 mph. Of this total, 40 hp was attributed to air resistance, and the balance of 39 hp was attributed to rolling resistance. All test work was conducted with the air conditioning and all other accessories turned off.

The bus was tested over three chassis cycles or operating conditions. These conditions/cycles included steady-state operation at hot idle, transient operation over the central business district (CBD) cycle, and transient operation on the bus cycle. The hot-idle steady-state was conducted with the transmission in "drive" and the brakes set. Emission samples were collected over a 15-minute period of hot-idle operation to allow adequate time for sample accumulation. Separate emission samples were taken over the CBD and the bus cycles.

The CBD cycle is one of four transit coach operating profile duty cycles proposed and used for evaluation of bus fuel economy.[6] For this work, the CBD cycle was composed of 14 repetitions of the basic cycle, which includes idle, acceleration, cruise, and deceleration modes. An example of this basic cycle is given in Figure 11, and it was repeated 14 times for a chassis driving cycle time of 580 seconds and a distance of 2.0 miles (3.2 km).

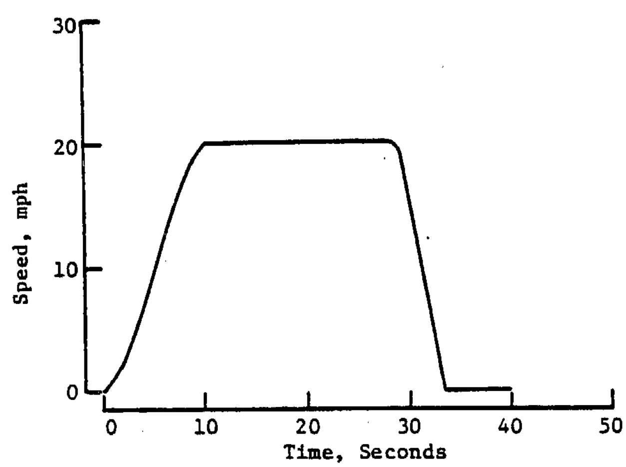

FIGURE 11. ONE SEGMENT OF THE CBD TEST CYCLE

The driving schedule developed by EPA to represent bus operation for research purposes is shown in Figure 12, and was used in this program as the "Bus Cycle."

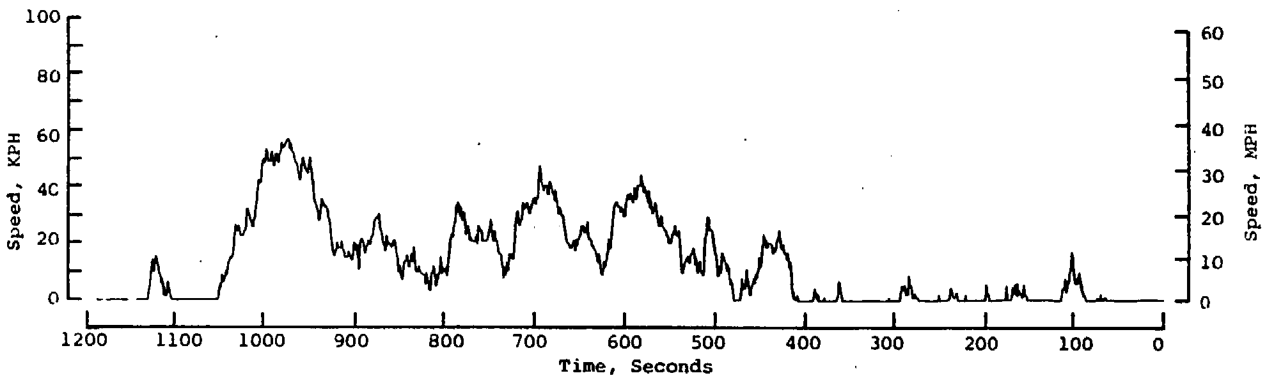

FIGURE 12. HEAVY-DUTY CHASSIS BUS DRIVING CYCLE

Of the 1191-second duration of the cycle, 394 seconds are idle, all of which is with the transmission in "drive." The distance of the bus cycle is 2.90 miles. The maximum speed called for by the cycle is 36 mph. The bus cycle contains many sharp accelerations and decelerations requiring full pedal deflection one moment and braking the next.

2. Emission Measurements

Emission measurements were based on procedures established for the 1984 transient testing of heavy-duty diesel engines(7), and on procedures outlined in the EPA "Recommended Practice for Determining Exhaust Emissions From Heavy-Duty Vehicles Under Transient Conditions."(4) Figure 13 shows the bus next to the single-dilution CVS routinely used in conjunction with heavy-duty chassis test work. All the engine exhaust gases were transferred to the CVS by a four-inch diameter exhaust tube, as shown in Figure 13. An in-line smokemeter was installed in the exhaust pipe connecting the bus exhaust outlet to the CVS entry. A CVS flowrate of about 3,000 SCFM provided adequate dilution for particulate sampling purposes during the chassis bus cycle. The single-dilution CVS has a capacity of 1,000 to 12,000 SCFM, and its dilution tunnel is 46 inches in diameter and 57 ft long. This system has the capacity to obtain three 20 x 20 in. filter samples of particulate matter along with additional samples needed for analysis of the total particulate. All testing was conducted with the CVS because particulate emissions were to be measured at all test conditions. Instrumentation for recording engine rpm and road speed of the bus, along with temperature and pressures of the exhaust stream, was installed on the bus.

Smoke levels were determined during "idle" in neutral, "snap-idle," and "stall." "Idle" smoke opacity was measured at curb-idle speed in neutral gear. "Snap-idle" peak smoke opacities were measured over W.O.T. acceleration of engine speed from curb idle to maximum governed speed while in neutral gear, repeated three times in rapid succession. "Stall" smoke opacity was measured when the engine achieved a stable speed, at full throttle, with the transmission in "drive" and the vehicle held stationary. In addition, use of the in-line smokemeter permitted smoke emissions monitoring over the transient bus cycle and the CBD cycle.

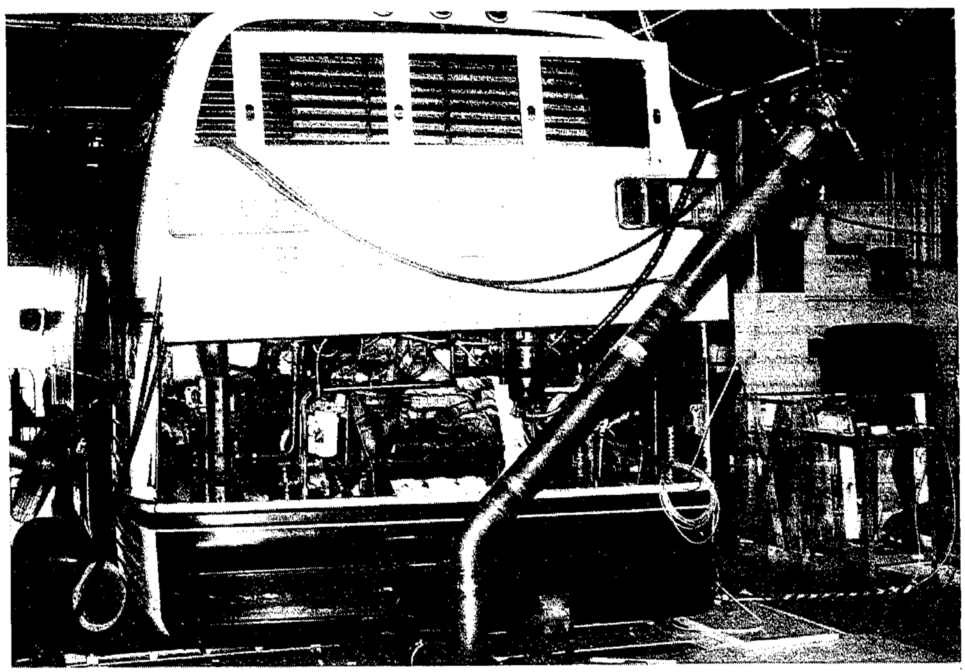

FIGURE 13. GMC RTS II 04 TRANSIT BUS POSITIONED FOR CHASSIS DYNAMOMETER TEST WORK

The transient Federal Test Procedure[7] (FTP) for heavy-duty diesel engines specifies that HC emissions be determined from integration of continuous concentration monitoring of the CVS-diluted exhaust. For continuous analysis of total hydrocarbons, the sample was transferred from the CVS to the Beckman 402 heated flame ionization detector (HFID) by a heated sample train. The heated sample train was maintained near 375°F. The procedure provides the option of determining CO and CO_2 from either dilute sample bags or integration of continuous concentration monitoring. Carbon monoxide and CO_2 levels were determined from proportional dilute exhaust bag samples. Concentrations of CO and CO_2 were determined by non-dispersive infrared (NDIR) instruments. NO_x emissions were determined from integration of continuous concentration monitoring of the CVS-diluted exhaust by a chemiluminescence (CL) instrument. NO_x correction factors for intake humidity were applied as specified in the 1984 transient FTP.[7]

Emission levels for HC, CO, CO_2, and NO_x were processed along with CVS flow parameters and bus operating parameters to compute mass emissions on the basis of distance and fuel usage. These computations were based on the equations specified in the Federal Register for exhaust emissions from gasoline or diesel exhaust.[7] Fuel consumption was computed on the basis of carbon balance.

Some selected individual hydrocarbons (IHC) were determined from dilute exhaust bag samples, taken over the transient bus cycle using the CVS. A portion of the CVS-diluted exhaust sample collected in a Tedlar bag was injected into a four-column gas chromatograph using a single flame ionization detector and dual sampling valve. The timed sequence selection valves allowed the baseline separation of air, methane, ethane, ethylene, acetylene, propane, propylene, benzene, and toluene.[8]

Aldehydes and ketones were determined over the transient bus cycle using the 2,4-dinitrophenylhydrazine (DNPH) method.[8] Dilute samples were taken from the main CVS dilution tunnel during transient testing using a heated Teflon sample line and filter maintained at 190°C (375°F). The procedure consists of bubbling filtered exhaust gas, dilute or raw, through glass impinger traps containing a solution of DNPH and HCl kept at 0°C. A liquid chromatograph is used to separate formaldehyde, acrolein, acetone, propionaldehyde, isobutyraldehyde, methylethylketone, crotonaldehyde, hexanaldehyde, and benzaldehyde.

Particulate emissions were determined from dilute exhaust samples utilizing various collection media and apparatus, depending on the analysis to be performed. Smoke and total particulate are related in that the relative level of smoke opacity indicate the relative level of particulate. The absence of smoke, however, does not indicate the absence of particulate. Particulate has been defined as any material collected on a fluorocarbon-coated glass fiber filter at or below a temperature of 51.7°C (125°F), excluding condensed water. The 51.7°C temperature limit and the absence of condensed water generally dictate that the raw exhaust be diluted, irrespective of engine operating mode. On the basis of the 51.7°C temperature limit, the CVS was run at approximately 3,000 SCFM during testing of the bus.

Total particulate mass samples were collected on 90 mm Pallflex T60A20 fluorocarbon-coated glass fiber filter media by means of a single-dilution technique. Gravimetric weight gain, representing collected particulate, was determined to the nearest microgram after the filter temperature and humidity were stabilized. This weight gain and recorded CVS flow parameters were used to calculate the total particulate mass emissions from the bus under test.

Sulfate, originating from the combustion of sulfur contained in the fuel, was collected as part of the total particulate matter on 47 mm Fluoropore (Millipore Corp.) fluorocarbon membrane filters. The level of sulfate contained in the total particulate sample was determined using the barium chloranilate (BCA) analytical method. A sample of total particulate matter was also collected on a 47 mm Fluoropore filter for the determination of trace elements such as calcium, aluminum, phosphorus, and sulfur by x-ray fluorescence. This analysis was conducted at the EPA, ORD Laboratories in Research Triangle Park, NC using a Siemens NRS-3 x-ray fluorescence spectrometer.

Diesel particulate generally contains significant quantities of condensed fuel-like or oil-like hydrocarbon aerosols generated in incomplete combustion zones. In order to determine the extent to which total particulate contains these various hydrocarbons, large particulate-laden filters (20 x 20 in.) were washed with an organic solvent, methylene chloride, using 500 ml soxhlet extraction apparatus. The dissolved portion of the "total particulate" carried off with the methylene chloride solvent has been referred to as the "soluble organic fraction" (SOF). All filter handling, extraction processes, and handling of concentrated SOF were carried out according to EPA recommended protocol.[9] The SOF may be composed of anything carried over in the extraction process, so its composition is also of interest. Generally, the SOF contains numerous organic compounds, many of which are difficult to isolate and quantify.

Further characterization of the soluble organic fraction from the bus in baseline configuration was planned to include analysis of benzo(a)pyrene, nitropyrenes, and Ames response, when samples from the bus fitted with a final trap/regeneration system were obtained. Since a final trap system was not established, these analyses were not carried out on the soluble organic fraction obtained from baseline testing of the bus.

3. Acceleration Performance

To judge performance with and without the various traps fitted to the bus, "full throttle" acceleration performance times were recorded along with temperature and pressure data. Acceleration performance was checked on the chassis dynamometer with a simulated inertia of 31,000 pounds. In contrast, over-the-road acceleration performance was conducted with the bus loaded with about 800 lb and the air conditioning off. The over-the-road accelerations were conducted on level roadway, in opposite directions, and were terminated after a speed of 40 mph was reached. Accelerations on the chassis dynamometer were carried out to 50 mph.

4. Noise Measurements

Because the proposed trap assembly was to replace the existing muffler, cursory noise measurements were conducted with the candidate trap assemblies located before, then after the turbocharger for comparison to noise levels measured during baseline operation of the bus. Noise measurements were conducted using the "FLAT" setting on the instrument to include all frequency bands. Exterior noise measurements were made at three points, during accelerations from a stop as illustrated in Figure 14.

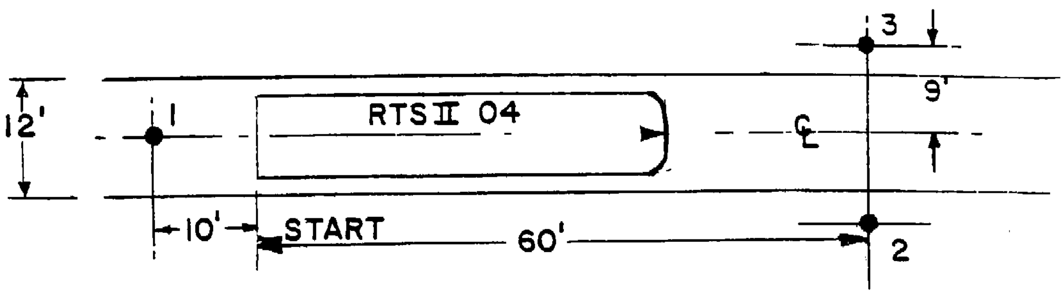

FIGURE 14. POSITIONS USED FOR NOISE MEASUREMENTS DURING WOT ACCELERATIONS FROM A STOP

5. Road Route

The bus was operated over a road route intended to present several different conditions to the bus; acceleration, hill climb, cruise, prolonged idle, and stop-to-stop operation. The purpose of using the 10-mile road route circuit, illustrated in Figure 15, was to expose the trap assembly to a variety of conditions expected to occur in normal usage. The first acceleration from the start of the route was to assess the effects of rapid heat input and temperature rise on the trap. The use of the hill climb (just under 5% grade) was to establish the maximum heat input available to the trap. The relatively level cruise condition followed by a deceleration, after the hill climb phase, allowed high levels of exhaust gas oxygen to be supplied to the "hot" trap in order to observe a probable failure mode of any trap.

Failure of a particulate trap can occur in a scenario such as the following:

1) much particulate has accumulated in the trap,
2) temperatures for regeneration are present, but the oxygen level is insufficient to promote regeneration due to high-load engine operation; then,
3) sudden vehicle deceleration causes engine motoring to quickly supply oxygen to the hot trap at reduced exhaust flow rate.

In this situation, trap failure occurs because the reduced exhaust flow rate is insufficient to transfer heat away from the trap during the ensuing regeneration.

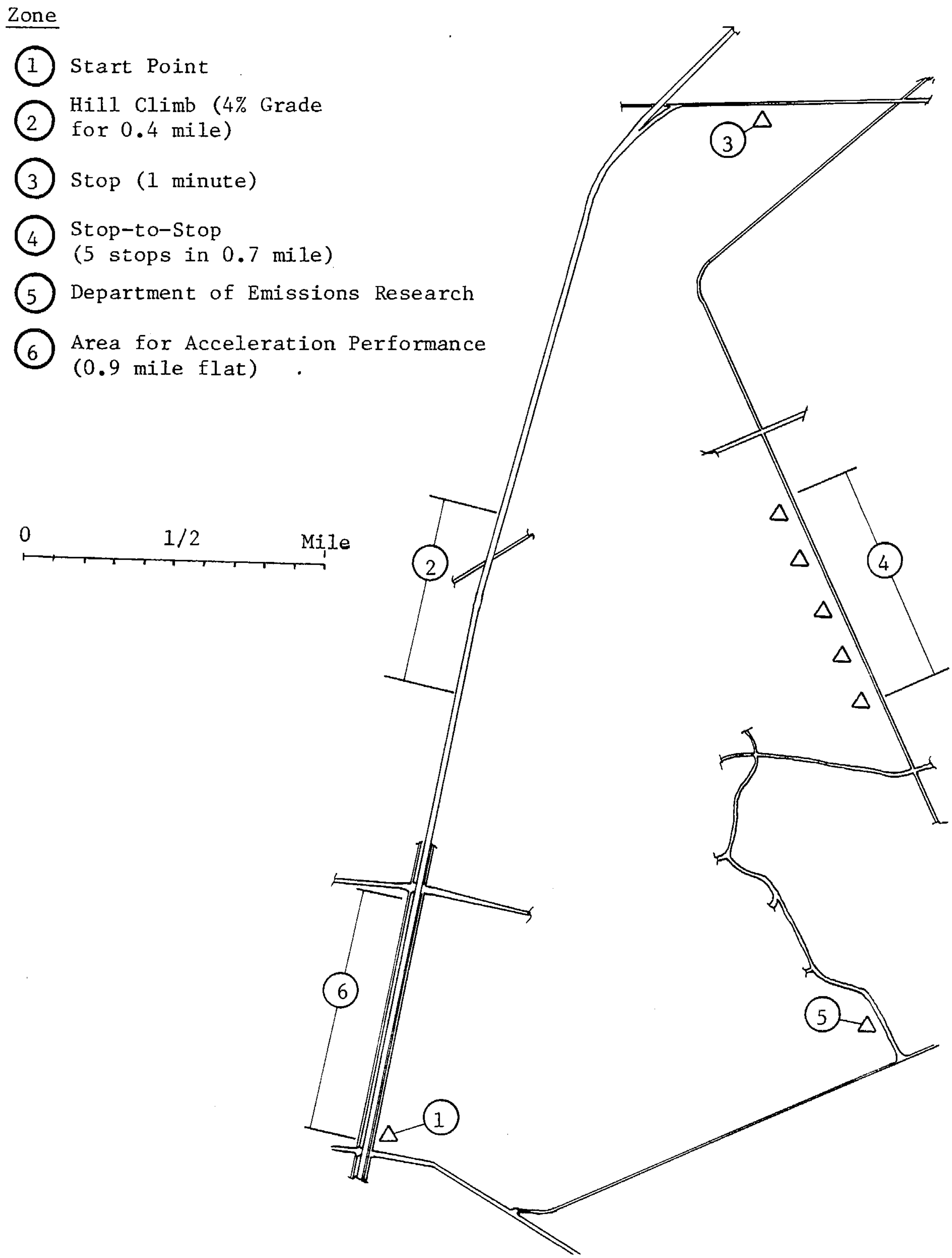

Figure 15. ROAD ROUTE FOR BUS TESTING

An idle-in-gear was held for one minute to observe fully warmed-up trap parameters. The bus was accelerated in a normal manner from this stop, and it followed normal traffic patterns to reach the stop-to-stop phase of the route. The stop-to-stop phase consisted of simulating five bus stops for passenger transfer within a relatively short distance. Each stop was held for ten seconds. This exercise was conducted to establish practical minimum temperatures that might be encountered in normal downtown operation scenarios. The remainder of the route was used to obtain general information and to complete the circuit, returning to the start of the road route.

IV. BASELINE EMISSIONS PERFORMANCE AND TRAP EVALUATION

After receiving the bus for test purposes, emphasis was placed on establishing the baseline operating parameters of the bus, determining its baseline emissions, and confirming the design of the trap assembly. The first trap was constructed and fitted to the bus for preliminary design check-out. After the trap design proved satisfactory for this program, emphasis was shifted to address the major problem with application of diesel particulate traps, reliable regeneration. Reliable regeneration must be accomplished periodically to assure that the trap does not become too burdened with diesel soot. Too much particulate loading results in large exotherms and high temperatures during regeneration that can damage or melt the trap.

Aside from establishing emission levels for comparison purposes, most other test work carried out under this program was designed to evaluate the catalyzed ceramic traps, identify problems, and establish methodologies to obtain reliable regeneration of the trap over normal operation of a city bus. It is important, in evaluating a particulate trap, to approximate the quantity of soot accumulated in the trap. The pressure drop across the trap increases as particulate is accumulated in the trap. For this reason, much of the following discussion deals with the relative changes in the differential pressure across the trap (Δp). The relative change in Δp or its square root ($\sqrt{\Delta p}$) indicates the relative soot loading in the trap. With detailed work, Δp or $\sqrt{\Delta p}$ across the trap at various conditions can be referenced to specific quantities of soot accumulation in the trap. This information is needed to provide signals that can be used to sense the need for regeneration.

The following discussion describes the progression of the program and results of various experiments conducted to promote regeneration of the catalyzed traps. Unfortunately, no continuous or semi-continuous regeneration could be assured over the normal operation of a city bus using selected catalyst coatings and periodic engine upset developed in this program. Therefore, the planned demonstration of one of the three catalyzed ceramic trap assemblies developed in this work was cancelled. No further development of this hardware is planned by the ARB. It is anticipated that the results of this research program will assist others and improve the chances for successful application of trap technology to heavy-duty diesel engines.

A. "As-Received" and Baseline Bus Emissions and Performance

Preliminary emissions and performance data were obtained from the bus in the "as-received" condition. Smoke emissions during accelerations of the bus on the road were almost imperceptible. Based on those observations it was decided that some preliminary work should be done to qualify the bus before a detailed emissions analysis was performed.

Over-the-road "full throttle" acceleration performance was recorded along with temperature and pressure data. Acceleration times from 0 to 10, to 20, and to 40 mph were approximately 4.6, 9.3, and 26.5 seconds, respectively (with the bus carrying a load of about 800 lb and the air conditioning off). The noise levels were measured with the bus in the "as-received" configuration, and with the exhaust exit pipe modified for CVS connection. For position No. 1 (directly behind the bus), position No. 2 (right side during drive-by), and position No. 3 (left side during drive-by), the readings were 94, 97, and 100 dB, respectively. Some of the temperatures and pressures noted during operation of the "as-received" bus over the road route are given in Table 7.

TABLE 7. PARAMETERS FROM THE BUS IN THE "AS-RECEIVED" CONDITION

Test Condition	Temperature to Turbocharger, °C	Pressure to Turbocharger, psi	Air Box Pressure, psi
Idle	185-250	0.6	1
Stop-to-Stop	220-350	0.6-12.0	1-14
Accel @ 20 MPH	320-350	12	14
Accel @ 40 MPH	380-390	12.6	14.1
Hill Climb (Max)	390-410	19-20	23-24

Following completion of the "as-received" road work, the bus was positioned on the chassis dynamometer for emissions test work. The bus was warmed up, and the dynamometer load was checked prior to operation over the bus cycle. Results from two preliminary runs of the bus cycle were (in gram/kilometer): HC, 2.0; CO, 3.2; NO_X, 13; and particulate, 1.3. Continuous monitoring of smoke opacity, during bus cycle operation indicated peaks from 5 to 10 percent smoke opacity with an average smoke opacity estimated to be about 3.5 percent. For the bus in the "as-received" condition, percentage smoke opacities were: 1.3 for idle, 7.0 for snap idle, and 4.0 for stall.

On the basis of these "as-received" data, the injection timing was retarded from 1.460 to 1.470 in., and the throttle delay was shortened from 0.636 to 0.504 inches. The prescribed adjustments were made to the engine, and preliminary emission testing was continued. Results from two runs of the bus cycle after adjustment to the engine were: HC, 1.6; CO, 6.4; NO_X, 12; and particulate, 1.7 grams/kilometer. Continuous monitoring of smoke opacity during bus cycle operation indicated peaks from 8 to 35 percent opacity, with the average smoke opacity estimated to be about 5.5 percent. The percentage smoke opacities were: 0.8 for idle, 35 for snap-idle, and 4.2 for stall. Based on the higher smoke opacities obtained after adjustment of the engine, approval to proceed with the detailed baseline emissions characterization was given.

Detailed baseline emissions measurements were conducted during chassis bus cycle testing of Bus No. 8296. Two bus cycles were conducted to establish baseline emissions of HC, CO, NO_X, and particulate. Two additional bus cycles were run to accumulate particulate mass sufficient for detailed analysis. Some of the emissions results obtained for the four bus cycles are given in Table 8.

TABLE 8. EMISSIONS FROM BUS 8296 ON THE BUS CYCLE, BASELINE CONFIGURATION

Test No.	Emissions, g/km HC	CO	NO_x	Part.	Distance, km	Fuel Usage kg	km/kg	Sulfate mg/km	Soluble Organic Fraction %	g/km
1	1.35	5.55	12.09	1.46	4.71	2.58	1.85	12	34.5	0.50
2	1.75	6.38	12.01	1.57	4.58	2.59	1.77	8.4	33.4	0.52
3	NR	NR	NR	1.75	4.63	NR	--	NR	34.9	0.61
4	NR	NR	NR	1.73	4.61	NR	--	NR	34.9	0.60
Avg.	1.55	5.96	12.05	1.63	4.63	2.58	1.80	10	34.4	0.56

NR = Not Run

Sulfate levels were very low, as expected with low-sulfur fuel. The soluble organic fraction (SOF) of the total particulate was established from extraction of large 20 x 20 in. particulate-laden filters using methylene chloride as a solvent. The percent SOF averaged 34 percent for baseline testing of the bus on the chassis bus cycle. Samples of extractables were placed in cold storage awaiting collection of comparable samples from the bus fitted with a trap regeneration system suitable for demonstration.

Dilute exhaust samples collected over bus cycle testing were analyzed for selected individual hydrocarbon species. The results, given in Table 9, indicate mostly ethylene and propylene, with a total of 160 mg/km for all species detected. Individual aldehydes, given in Table 10, were determined using the DNPH method. Formaldehyde, acetaldehyde, and acetone made up the bulk of the aldehyde emission which totaled about 350 mg/km.

TABLE 9. INDIVIDUAL HYDROCARBON EMISSIONS FROM BUS 8296, BASELINE CONFIGURATION, BUS CYCLE

Individual Hydrocarbon	Emissions, mg/km Test 1	Test 2	Avg.
Methane	0	0	0
Ethane	2.5	2.8	2.7
Ethylene	85	88	86
Propane	12	0	6.0
Propylene	61	76	68
Total IHC	160	170	160

Levels of methane were below background levels
Levels of acetylene, benzene, and toluene were below the limit of detection

TABLE 10. ALDEHYDE EMISSIONS FROM BUS 8296, BASELINE CONFIGURATION, BUS CYCLE

Individual Aldehyde	Bus Cycle, mg/km		
	Test 1	Test 2	Avg.
Formaldehyde	98	170	140
Acetaldehyde	82	44	63
Acrolein	26	--	13
Acetone	68	140	100
Crotonaldehyde	11	--	6.0
Isobutyraldehyde + MEK	31	--	16
Benzaldehyde	18	--	9.0
Hexanaldehyde	14	--	7.0
Total	350	350	350

Elemental analysis of total particulate samples collected on the bus cycle, the CBD, and hot-idle operation are given in Table 11. The elements sulfur, iron, calcium, copper, magnesium, zinc, and phosphorus were noted. Most of these elements, including sulfur, likely originate from the crankcase oil. Lube oil used in this program was Quaker State SAE 40 with CD rating.

The bus also was operated over the Central Business District (CBD) chassis cycle and a hot-idle condition with the transmission in "drive" to obtain baseline emissions data for reference purposes. Results from the CBD cycle were: HC, 1.5; CO, 5.1; NO_x, 13; and particulate 1.6 g/km. These emission levels were very similar to those obtained on the chassis bus cycle. Emission levels on the hot-idle are given on a fuel specific basis, and were: HC, 5.5; CO, 7.5; NO_x, 27; and particulate, 2.0 g/kg fuel.

Baseline acceleration performance was also checked on the chassis dynamometer for reference purposes. With a simulated inertia of 31,000 lb, the acceleration times from 0 to 10, to 20, and to 40 mph were approximately 4.8, 10.5, and 31.3 seconds, respectively. The bus was removed from the chassis dynamometer for road work. Over-the-road acceleration times from 0 to 10, to 20, and to 40 mph for the bus in the baseline configuration were approximately 3.8, 8.4, and 25.0 seconds, respectively. These times were similar to those noted for the "as-received" configuration, but slightly shorter.

The bus, in its baseline configuration, was operated over the road route described in the Test Procedure section of this report. Some of the pertinent temperatures and pressures noted during the road route are given in Table 12. Results were similar to those reported for the "as-received" configuration, although peak pressures were about 1 psig greater. The noise levels obtained for reference position Nos. 1, 2, and 3 were 97, 97, and 100 dB, respectively. The slight increase in noise level directly behind the bus (position 1) was likely a result of test-to-test variation.

TABLE 11. METALS AND SULFUR FROM PARTICULATE FROM BUS 8296 IN THE BASELINE CONFIGURATION OVER THE BUS CYCLE

Individual Elements	Total Particulate, wt. % Bus Cycle	CBD Cycle	Hot Idle	Detection Limit, wt. %
Al	a	a	a	0.005
As	a	a	a	0.083
Ba	a	a	a	0.022
Br	a	b	b	0.161
Ca	0.153	0.097	0.248	0.005
Cd	a	a	a	0.004
Cl	0.010[c]	a	a	0.005
Co	a	a	a	0.049
Cu	0.155	0.231	b	0.054
Cr	b	b	b	0.089
Fe	0.491	0.510	1.447	0.049
Hg	a	a	a	0.290
K	0.015[c]	a	a	0.004
Mg	0.047	0.089	0.080	0.008
Mn	a	b	a	0.049
Mo	a	b	b	1.005
Na	a	a	a	0.087
Ni	b	b	b	0.047
P	0.043	0.076	b	0.008
Pb	a	b	b	0.581
Pt	a	a	a	0.201
S	0.322	0.506	0.347	0.009
Sb	a	a	a	0.013
Se	a	a	a	0.094
Si	0.028[c]	a	a	0.016
Sn	a	a	a	0.036
Sr	a	b	b	0.380
Ti	a	b	a	0.008
B	a	a	a	0.036
Zn	0.087[c]	0.204	b	0.054

[a]concentration below the detection limit
[b]element was detected but was below the level of quantitation (3 x detection limit)
[c]average of two determinations, but only one indicated a level sufficient for quantitation

TABLE 12. PARAMETERS FROM THE BUS IN THE BASELINE CONDITION

Test Condition	Temperature to Turbocharger, °C	Pressure to Turbocharger, psi	Air Box Pressure, psi
Idle	190-240	0.7	1
Stop-to-Stop	225-380	0.7-13.2	1-15
Accel @ 20 MPH	330-355	13.3	15.3
Accel @ 40 MPH	375-385	13.8	15.8
Hill Climb (Max)	415	21	25

B. Trap No. 1

The completed Trap No. 1, without catalyst coating, was positioned in the engine compartment with exhaust piping set to divert the exhaust around the trap assembly (trap bypassed). This allowed engine operation to reposition the bus on the chassis dynamometer without affecting the trap.

It was assumed that methods of engine upset should be studied in case it proved necessary to promote regeneration of the trap. Three 3/4 in. air lines were run from the air box to the blower inlet of the engine. These lines were fitted with valves so that compressed intake air from the air box could be vented to atmosphere or returned to the blower inlet. Figure 16 shows the valves positioned at the rear of the engine compartment and the tubes routed up to the turbocharger outlet or blower inlet. It was anticipated that venting the air box would cause dramatic increases of engine exhaust gas temperature and CO level over the whole operating range of the engine. Both of these increases were expected to favor regeneration of a catalyzed trap. Returning compressed air from the air box to the blower inlet (blower bypass) was expected to raise the exhaust gas temperature and CO level mostly during low power operation, with very little effect on the exhaust gases during high power operation.

After completing the installation of Trap No. 1, along with the valves and tubing necessary to conduct experiments with air box bleed, the bus was repositioned on the dynamometer with all exhaust gases diverted around the trap assembly. Engine operation was noticeably noisier without the muffler, even though exhaust gases were routed to the CVS. Following dynamometer set-up, dilute HC, CO, NO_x, and particulate emissions were measured over the bus cycle, CBD, and hot-idle operation without the muffler, with the trap bypassed. In addition, raw HC, CO, CO_2, NO_x, and O_2 concentrations of the exhaust gases enroute to the turbocharger were monitored over various engine operating conditions.

Experiments with air box bleed were conducted using the CBD cycle. Results from those experiments in which air was either vented to atmosphere or routed back to the turbocharger inlet are given in Table 13. Air box bleed had very little effect on parameters monitored during steady-state operating conditions such as hot-idle and 25 mph cruise. Greatest differences occurred during accelerations, such as found on the CBD cycle. The values in Table 13

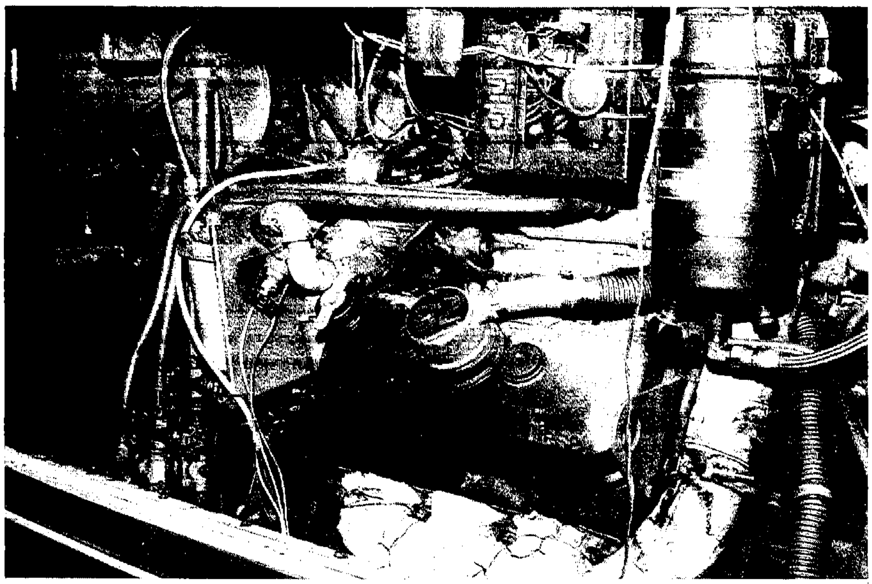

FIGURE 16. VIEW OF VALVES AND TUBING USED TO VARY ENGINE BREATHING ALONG WITH VIEW OF VALVE INSTALLED TO STOP WATER FLOW THROUGH AFTERCOOLER

TABLE 13. RESULTS OF AIR BOX BLEED ON VARIOUS ENGINE PARAMETERS, CBD OPERATION OF BUS 8296 WITHOUT MUFFLER

Valves Open to Atm. or Turbo	Air Box Press. psig	Turbo Inlet Temp. °C	Turbo Inlet Temp. psig	Turbo Boost Press. psig	Smoke Opacity Peak Height %	Smoke Opacity Avg.[a] Level %	Raw CO[c] Peak Height %	Raw CO[c] Base[b] Time sec
0	11.7	340	10.5	9.6	18	3	0.08	8
1 to Atm.	9.0	390	8.1	7.1	28	5	0.17	10
2 to Atm.	6.0	430	5.8	4.7	45	15	0.17	15
3 to Atm.	4.5	485	4.5	3.3	65	33	0.33	20
1 to Turbo	12.0	375	11.1	10.5	22	3	0.12	5
2 to Turbo	11.7	380	10.2	10.0	28	3	0.18	10
3 to Turbo	11.3	390	10.2	10.2	45	3	0.25	10

[a]average level is the level noted after the effect of the peak had deteriorated
[b]base time is the approximate time under the peak
[c]raw CO measured before the turbocharger

represent peak values obtained on the CBD cycle, and were generally read during the 10-second mph acceleration of the bus from 0 to 10 mph. Air box bleed was expected to increase exhaust temperatures and increase CO levels. Reducing the air box pressure from 11.7 to 4.5 psig, by opening three valves to atmosphere, caused the exhaust gas temperature enroute to the turbocharger to increase from 340 to 485°C. Levels of CO increased substantially, from 800 to 3300 ppm, and remained near the higher level for nearly 20 seconds of the CBD cycle. Smoke levels increased substantially to 65 percent (peak), tapering down to some 33 percent opacity over the cruise portion of the CBD cycle.

Routing air box gases back to the blower inlet (intake air turbocharger outlet), by opening three different valves, increased the temperature of the exhaust gases enroute to the turbocharger to 390°C. Levels of CO also were increased, but not to the extent noted when venting the air box gases to atmosphere. Smoke levels also were high initially at 45 percent opacity, but tapered down to 3 percent during the CBD cycle. Further experiments with air box bleed schemes, intended to increase exhaust temperature and CO levels, were planned when catalyzed trap assemblies were installed. Evaluation of air box bleed with an uncatalyzed trap assembly would only have demonstrated faster particulate load-up.

After smoke opacity and acceleration performance were measured, and after preliminary air box bleed experiments were conducted without the muffler, exhaust piping was rerouted, placing the uncatalyzed Trap No. 1 before the turbocharger. Gaseous, particulate, and smoke emissions were measured, along with engine parameters. Trap differential pressure (Δp), and trap inlet and outlet temperatures were monitored over the various test cycles. An engine idle condition of 1500 rpm (in neutral) was initially chosen for trap Δp reference condition. Clean trap assembly Δp at 1500 rpm was 18 in. H_2O.

After vehicle operation for dynamometer warm-up, and after tests consisting of the bus cycle, CBD, hot-idle, three W.O.T. accelerations to 50 mph for performance, and smoke opacity measurements, the Δ p at 1500 rpm increased to about 24 in. H_2O.

Prior to conducting a regeneration of the trap, a borescope inspection device was used to examine inlet and outlet faces of both ceramic filter substrates. Approximately 7 to 10 channels on each of the two substrate assemblies appeared to be leaking. The appearance of black exit channels located along the seam, where the blocks of ceramic elements were cemented together, indicated that some minor leakage of exhaust gases occurred through the ceramic filter assemblies.

Regeneration (or cleaning) of Trap No. 1 was accomplished using an acetylene torch flame placed in the exhaust stream, as shown in Figure 17, while the engine operated at curb idle (in neutral). A trap inlet temperature of about 530°C was maintained for about 2 minutes, then the flame was turned off. After the trap cooled its Δp at 1500 rpm was down to 18.5 in. H_2O, indicating that the trap had been regenerated.

The bus was operated over repetitive bus and CBD cycles for one hour to partially load the trap, then gaseous and particulate emissions were measured over a bus cycle and a CBD cycle. After accumulating approximately 23 km (14 miles) of cyclic operation, the trap Δp at 1500 rpm increased to about 23 in. H_2O. Using an acetylene torch for regeneration, the engine idle exhaust gases entering the trap were brought to 535°C for about 2 minutes. After cooling, the trap Δp at 1500 rpm measured 21 in. H_2O. This Δp indicated that the substrates were not completely clean, and that a partial regeneration had occurred.

A visual inspection of the inlet faces of the ceramic filter substrates was conducted. It appeared that the high temperature gases (provided for regeneration) were favoring the perimeter of the substrate, leaving a black spot (about 3 inches in diameter) located in the center of the substrate faces. Figure 18 shows the inlet and outlet of Trap No. 1 with the exhaust transfer tubes removed. The opening shown in the upper portion of the figure is the inlet to the trap. The lighter portion is the uncatalyzed substrate after regeneration with the acetylene torch.

Exhaust tubing was rerouted so that the trap was effectively placed after the turbocharger. Trap Δ p at 1500 rpm (relatively clean condition) was measured as 20 in. H_2O. As before, gaseous, particulate, and smoke emissions were measured, along with engine parameters. After operation for dynamometer warmup, bus cycle, CBD, hot-idle, three W.O.T. accelerations to 50 mph, and smoke opacity measurements, the trap Δp at 1500 rpm increased to 23 in. H_2O. Trap Δ p recorded during snap-idle operation for smoke opacity measurement was about 50 in. H_2O.

Using an acetylene torch for regeneration, the trap Δ p at 1500 rpm was reduced to about 21 in. H_2O. Again, the trap was only partially cleaned. After two bus cycles and one CBD cycle, the trap Δp was 22 in. H_2O at the 1500 rpm reference point, and 54 in. H_2O during snap-idle operation. After another bus

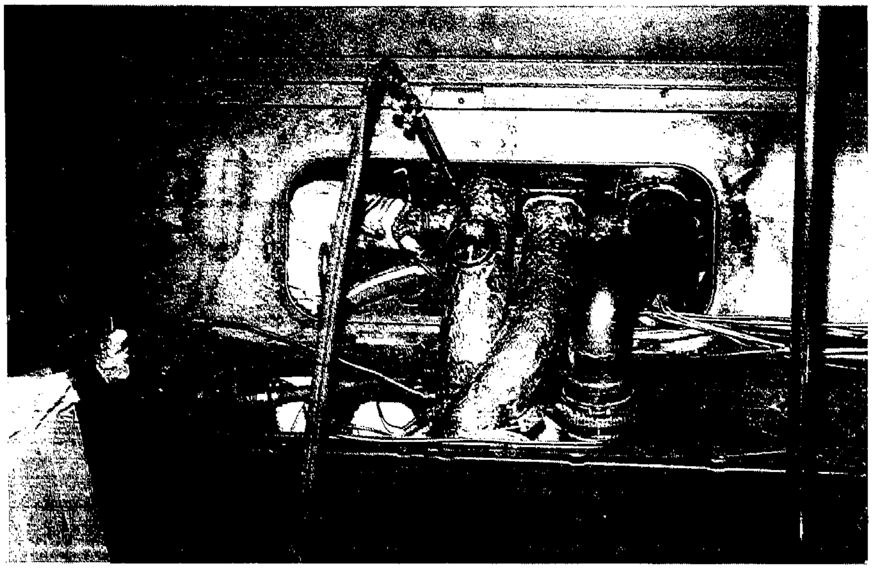

FIGURE 17. REGENERATION OF UNCATALYZED TRAP NO. 1
WITH AN ACETYLENE TORCH DURING ENGINE IDLE

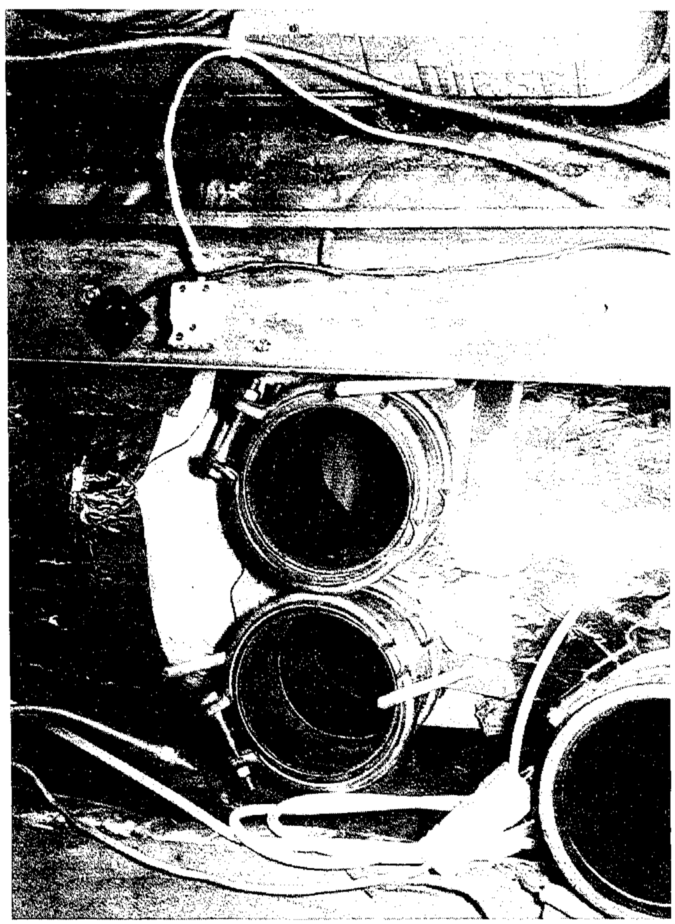

FIGURE 18. VIEW OF TRAP NO. 1 INLET AND OUTLET AFTER REGENERATION

cycle and CBD cycle were run, the Δp for snap-idle was about 62 in. H_2O. Following a regeneration in which high trap inlet temperature conditions were maintained for approximately 5 minutes to ensure that the trap assembly was cleaned, the trap Δp at snap-idle was about 53 in. H_2O.

Trap Δp measurement at the 1500 rpm reference condition was dropped in favor of measuring the Δp during the snap-idle condition, because it was difficult to hold the engine speed steady at 1500 rpm with no load. Snap-idle relies on the engine's governor to hold a steady, repeatable, high-idle speed. In addition, trap Δp measurement also varies with the temperature of the trap inlet gas stream, so measurements were typically made after the trap reached about 200°C. The bus was removed from the dynamometer and was prepared for road work with Trap No. 1 in the after turbocharger position.

Comparative emission levels from the bus in several configurations are given in Tables 14, 15, and 16 for the bus cycle, the CBD cycle, and the hot-idle steady-state, respectively. These emission levels are based on two runs each of the bus cycle and CBD cycle, and a single run of the hot-idle condition. There was little change in emissions without the muffler. When Trap No. 1 was installed in the before turbocharger position, CO levels on the bus and CBD cycles tended to increase by a factor of almost 2), while NO_x levels tended to decrease. Overall, particulate trapping efficiency of Trap No. 1 ranged from 90 percent on the hot-idle, to 75 percent on the CBD and 82 percent on the bus cycle.

Locating Trap No. 1 after the turbocharger appeared to have little effect on the emission levels of HC and CO. Levels of NO_x were lower with the trap located after the turbocharger. Total particulate reduction, or trapping efficiency, was greatest during the idle condition at 85 percent, followed by 82 percent on the bus cycle and 81 percent on the CBD cycle.

Results of smoke measurement during idle, snap-idle and stall conditions are given in Table 17. Operation with reduced backpressure, by removal of the muffler, showed a trend to lower smoke levels. With Trap No. 1 in either position, visible smoke was essentially eliminated. Recall that the stall smoke reading was taken after stall rpm was achieved. The stall smoke levels noted in Table 17 were generally preceded by a "puff" of smoke near the level recorded during the snap-idle condition. It is important to note that with Trap No. 1 in either location relative to the turbocharger, the "puff" of smoke was essentially eliminated. Similarly, for both bus and CBD cycles, no smoke emission above the 1.5 percent opacity level was noted.

Application of a particulate trap was expected to affect acceleration performance. Several W.O.T. acceleration times are given in Table 18. Surprisingly, there was not much variation (generally less than 10 percent) in acceleration times as compared to the baseline configuration. Although no major change in acceleration performance was observed with the trap in place, changes in several pressures and temperatures were noted as shown in Table 19.

The values given in Table 19 were read from charts of CBD cycle operation, and represent peak values noted during the acceleration of the bus from 0 to 20 mph. "Boost pressure" is the pressure between the turbocharger

TABLE 14. EMISSIONS FROM BUS 8296 ON THE CHASSIS BUS CYCLE WITH TRAP NO. 1

Bus Configuration	Emissions, g/km				Fuel Usage	
	HC	CO	NO_x	Part.	kg	km/kg
Average Baseline	1.55	5.96	12.05	1.63	2.58	1.80
Without Muffler	1.5	4.3	11	1.6	2.5	1.9
Trap No. 1 Before Turbo	2.5	9.5	11	0.3	2.3	2.0
Trap No. 1 After Turbo	1.7	7.0	10	0.3	2.4	2.0

TABLE 15. EMISSIONS FROM BUS 8296 ON THE CBD CYCLE WITH TRAP NO. 1

Bus Configuration	Emissions, g/km				Fuel Usage	
	HC	CO	NO_x	Part.	kg	km/kg
Average Baseline	1.5	5.1	13	1.6	1.9	1.7
Without Muffler	1.5	3.5	13	1.5	1.9	1.8
Trap No. 1 Before Turbo	1.2	14	12	0.4	1.9	1.8
Trap No. 1 After Turbo	1.4	6.3	11	0.3	1.8	1.8

TABLE 16. EMISSIONS FROM BUS 8296 ON IDLE WITH TRAP NO. 1

Bus Configuration	Emissions, g/km				Fuel Usage	
	HC	CO	NO_x	Part.	kg	km/kg
Average Baseline	5.5	7.5	27	2.0	0.9	--
Without Muffler	6.4	6.1	27	2.2	0.9	--
Trap No. 1 Before Turbo	5.9	8.1	27	0.2	0.9	--
Trap No. 1 After Turbo	4.6	6.2	25	0.3	0.9	--

TABLE 17. PERCENT SMOKE OPACITIES FROM BUS 8296

	Baseline	Without Muffler	Trap No. 1 Before Turbo	Trap No. 1 After Turbo
Idle	0.8	0.4	0.3	0.3
Snap Idle	35	27	2.0	1.0
Stall	4.2	2.1	1.2	1.3

TABLE 18. ACCELERATION TIMES FROM BUS 8296 ON THE DYNAMOMETER WITH AN INERTIA OF 31,000 POUNDS WITH TRAP NO. 1

MPH	Baseline	Without Muffler	Trap No. 1 Before Turbo	Trap No. 1 After Turbo
0-10	4.8	4.3	4.3	4.5
0-20	10.5	9.8	10.4	10.2
0-40	31.3	31	33	31
0-50	50	54	52	48

TABLE 19. PEAK VALUES OF PARAMETERS MONITORED DURING CBD OPERATION OF BUS 8296

	Baseline	No Muffler	Trap No. 1 Before Turbo	Trap No. 1 After Turbo
Air Box Press., psig	14.1	12.0	8.7	12.5
Boost Press., psig	11.6	9.6	5.1	8.6
Temp to Turbo, °C	345	345	285	410
Press. to Turbo, psig	13.8	10.7	6.8[b]	11.0
Temp to Trap, °C	--	--	405	310
Temp from Trap	--	--	285	210
Press. to Trap, psig	--	--	8.4	2.3
Trap Δp, in H_2O	--	--	44[a]	51[a]

[a]clean trap - measured on CBD
[b]computed, press. to trap

and the blower. The difference between the "boost pressure" and the "air box pressure" indicates the relative amount of compression work that must be input by the positive displacement blower. For the "baseline" and the "without muffler" configurations, the differences were 2.5 and 2.4 psig, respectively. For the before and after turbocharger configurations, the differences were 3.6 and 3.7 psig, respectively. In addition, the temperature of the exhaust gases after both banks are combined was 345°C without the trap, but increased to about 405 and 410°C with the trap positioned before and after the turbocharger, respectively. These results indicate that the air flow through the engine was reduced equally when the trap was used in either location.

After completing emission testing of the bus fitted with the uncatalyzed trap assembly (Trap No. 1), road evaluation of the trap was begun. The bus was operated with the trap in the after turbocharger configuration, then in the before turbocharger configuration. There was a 15°C difference in ambient road test temperatures between evaluations as listed in Table 20. Generally, the bus acceleration and noise performance were not noticeably different from baseline. Results from these evaluations are listed in Tables 21 and 22, respectively. There were only small differences in acceleration times on the road, indicating a slight loss in performance with the trap in either position, relative to baseline. Noise levels with the trap in either position were slightly below baseline levels.

Temperatures and pressures monitored during road evaluation are given in Tables 23, 24, and 25. During accelerations with the trap before the turbocharger, air box pressures were considerably lower than for baseline. In addition, exhaust pressure to the turbocharger and boost pressure were also reduced with the trap located before the turbocharger. Temperatures to the turbocharger were somewhat lower than for baseline when the trap was positioned before the turbocharger. Relatively high trap inlet temperatures were available with the trap located before the turbocharger. Although there were significant differences in the temperatures and pressures noted with the trap before the turbocharger compared to baseline operation, the acceleration performance was similar to baseline. It is likely that when the trap substrate is hot and the trap Δp is low, the before turbocharger trap position may not affect engine performance appreciably.

Locating the trap after the turbocharger allowed the air box pressure, pressure at the turbocharger, and temperature at the turbocharger to approach the baseline levels. Temperatures at the turbocharger were slightly increased. Acceleration times with the trap positioned after the turbocharger were most like those obtained for baseline operation; however, temperature at the trap ranged from 150 to 330°C, making it more difficult to achieve the high temperatures needed for regeneration.

After operating the bus equipped with Trap No. 1 after the turbocharger for approximately 30 miles over the road, trap Δp measured at the snap-idle reference condition increased from approximately 41 to 50 in. H_2O (corresponding to an increase from 22 to 26 in. H_2O measured at 1500 rpm). The uncatalyzed trap assembly was regenerated at the laboratory using an acetylene torch.

TABLE 20. AMBIENT CONDITIONS DURING ROAD EVALUATION

Test Configuration	Temperature Dry, °C	Wet, °C	Barometer in Hg	Test Date
Baseline	26	22	29.26	11/8/85
Trap No. 1 After	14	10	29.42	2/13/86
Trap No. 1 Before	22	16	29.25	2/14/86

TABLE 21. ACCELERATION TIMES OF BUS 8296 ON THE ROAD (NO BALLAST ADDED)[a]

	Time in Seconds		
Speeds, mph	Baseline	Trap No. 1 Before Turbo	Trap No. 1 After Turbo
0-10	3.8	3.9	4.0
0-20	8.4	9.0	8.8
0-40	25	29	27

[a]bus loaded with 500 to 800 lbs, air conditioning off

TABLE 22. ACCELERATION NOISE LEVELS FROM BUS 8296 ON THE ROAD

	Noise Level, db		
Position[a]	Baseline	Trap No. 1 Before Turbo	Trap No. 1 After Turbo
1	97[b]	94	96
2	97	95	94
3	100	96	95

[a]position 1 is 10 ft. behind bus, position 2 is on the right side of the bus during drive-by, and position 3 is on the left side of the bus during drive-by.
[b]had been recorded as 94 in the "as received" condition

TABLE 23. PARAMETERS FROM ROAD WORK OF BUS 8296 IN BASELINE CONFIGURATION

	Idle	Stop to Stop	Accel @ 20 mph	Accel @ 40 mph	Hill Climb (Max.)
Air Box Press, psig	1	1-15	15.3	15.8	25
Boost Press, psig	0.4	0.4-13	12.9	13.5	16.5
Temp. to Turbo, °C	190-240	225-380	330-355	375-385	415
Press. to Turbo, psig	0.7	0.7-13.2	13.3	13.8	21

TABLE 24. PARAMETERS FROM ROAD WORK OF BUS 8296 WITH TRAP NO. 1 BEFORE TURBO

	Idle	Stop to Stop	Accel @ 20 mph	Accel @ 40 mph	Hill Climb (Max.)
Air Box Press, psig	1	1-11	7.8	9.5	25
Boost Press, psig	0.3	0.5-6.6	4.1	5.4	13.7
Temp. to Turbo, °C	280	310-330	250	260	410
Press. to Turbo, psig[a]	0.6[a]	0.6 - 7.5[a]	7.2[a]	6.4[a]	18[a]
Temp. to Trap, °C	210	230-430	400	445	450
Temp. from Trap, °C	300	310-330	250	280	410
Press. to Trap, psig	0.8	0.9-9.3	7.2	8.7	21
Trap Δp, in H_2O	6	7-50	36	63	74

[a]calculated from "pressure to trap" minus "trap Δp"

TABLE 25. PARAMETERS FROM ROAD WORK OF BUS 8296 WITH TRAP NO. 1 AFTER TURBO

	Idle	Stop to Stop	Accel @ 20 mph	Accel @ 40 mph	Hill Climb (Max.)
Air Box Press, psig	1	1-15	14.1	14.7	22
Boost Press, psig	--	--	--	--	--
Temp. to Turbo, °C	175-205	200-420	400	430	450
Press. to Turbo, psig	0.8	0.8-13.0	12.6	13.1	18
Temp. to Trap, °C	155-190	200-300	285	310	330
Temp. from Trap, °C	175-210[a]	210-230	220	235	280
Press. to Trap, psig	0.2	0.2-2.4	2.2	2.4	3.5
Trap Δp, in H_2O	5.0	6.0-63	56	61	90

[a]higher than inlet due to thermal inertia

Overall, the results obtained with uncatalyzed Trap No. 1 indicated that the design of the trap assembly was satisfactory. These results demonstrated that high trapping efficiencies were feasible, and that sizing of the unit appeared to be satisfactory. Acceleration performance was not adversely affected by presence of the trap. Road work confirmed that locating the trap before the turbocharger provided higher trap inlet temperatures than if the trap were located after the turbocharger. There were only minor differences in noise and acceleration performance of the bus fitted with the trap in either location.

Trap No. 1 was removed from the bus. The trap was carefully disassembled and the two EX-47 ceramic filter substrate pieces were removed from their cans. The ceramic substrates appeared to be in good condition, and were subsequently shipped for catalyzing so that they could be used to construct Trap No. 4.

C. Trap No. 2

Two EX-66 ceramic filter substrates, catalyzed with formulation "A," were built into Trap No. 2. This unit was mounted in position, and the bus was repositioned on the chassis dynamometer with all exhaust gases bypassing the trap (without muffler configuration). Emission measurements were made without the muffler over two bus cycles, one CBD cycle, and hot-idle conditions. Overall bus operation was satisfactory without the muffler; however, emissions of HC, CO, NO_x, particulate, and smoke all appeared to be slightly greater than previously obtained without the muffler. In addition, exhaust gas temperature to the turbocharger was about 60°C higher during W.O.T. acceleration to 50 mph on the chassis dynamometer. No problems with the engine or dynamometer setup were noted. The reason for the small increase in emissions and exhaust temperature compared to the previous run made without the muffler was uncertain, but the magnitudes of the changes were considered relatively small. The changes were not expected to adversely affect the evaluation of Trap No. 2.

The exhaust gases were routed through Trap No. 2 in the before turbocharger configuration. Initial trap Δp at 1500 rpm was 11 in. H_2O. Trap Δp was 19 in. H_2O at snap-idle, and about 42 in. H_2O at 50 mph. A bus cycle, CBD cycle, hot-idle, smoke, and W.O.T. accelerations were conducted for emissions, temperature data, and pressure data. After this first sequence of bus operation, trap Δp at the 1500 rpm reference condition increased to 19 in. H_2O. At snap-idle, the Δp was 35, and at 50 mph it was, 48 in. H_2O. Although the trap Δp measured at 1500 rpm and snap-idle had almost doubled, the Δp measured at 50 mph did not increase in proportion.

Based on the moderate changes in Δp, another emission test sequence was conducted. Following the second sequence (consisting of a bus cycle, CBD cycle, hot-idle, smoke, and W.O.T. accelerations) conducted for emissions and for temperature and pressure data, trap Δp at 1500 rpm increased to 22 in. H_2O. At snap-idle, trap Δp increased to 40 in. H_2O; and at 50 mph, it measured 55 in. H_2O.

In order to accumulate more emissions information, a third sequence was run, including a bus cycle, a CBD cycle, and hot-idle operation. In addition, another bus cycle, CBD cycle, bus cycle, and CBD cycle were run to experiment with trap loading. High exhaust heat conditions such as 50 mph operation were not run to avoid a potential regeneration condition. At the end of this third sequence, the trap Δp measured 31 in. H_2O at 1500 rpm and 56 in. H_2O during the snap-idle.

In addition to checking Δp after a given test sequence, the peak values of trap Δp on the CBD cycle were tracked as testing progressed. After approximately five miles into the first sequence, trap Δp peaks on CBD operation were about 40 in. H_2O. After another 17 miles of test work, peak Δp values on the CBD (second sequence) increased to about 45 in. H_2O. With another 17 miles, the trap Δp on the CBD (during the third sequence) increased to 48 in. H_2O. Accumulating ten more miles of transient operation raised the trap Δp on CBD operation to 58 in. H_2O.

The main reason for monitoring the trap Δp is to infer the level of accumulated soot in the trap. It is difficult to reliably assess trap loading on the basis of Δp; because the Δp is affected by the volume and velocity of exhaust gases passed through the trap, making it very dependent on engine operating conditions. In order to assess the trap particulate loading, it appears that comparing change in the square root of the Δp may be more meaningful than examining the relative change in Δp.

Comparing the square roots of the Δp obtained at 1500 rpm <u>before</u> the initial test sequence to that obtained after the sequence showed 31 percent increase. A 36 percent increase in $\sqrt{\Delta p}$ occurred at snap-idle, but only a 7 percent increase in $\sqrt{\Delta p}$ occurred for the 50 mph condition. Comparing the square roots of the Δp from before and after the second test sequence showed the following: $\sqrt{\Delta p}$ at 1500 rpm increased 8 percent, $\sqrt{\Delta p}$ for snap-idle increased 7 percent, and $\sqrt{\Delta p}$ at 50 mph increased 7 percent. Because the changes in the $\sqrt{\Delta p}$ were more uniform after the second sequence than after the initial sequence, it is likely that the initial Δp readings, taken during engine warm-up with the new Trap No. 2, represent only "new" trap conditions and not realistic values to judge relative trap loading.

A 19 percent change in the $\sqrt{\Delta p}$ at 1500 rpm, an 18 percent change in $\sqrt{\Delta p}$ for snap-idle, and a 21 percent change in $\sqrt{\Delta p}$ on CBD operation was computed using Δp values measured after initial operation for reference. The 21 percent change noted in the square root of the Δp on CBD operation is important for future reference with regard to trap regeneration experiments.

Because the Δp across Trap No. 2 located <u>before</u> the turbocharger only increased during the three test sequences, no regeneration occurred under the test conditions encountered on the chassis dynamometer. It was assumed that an equilibrium condition would not be reached during the chassis test sequences run for emissions, and that regeneration of the trap would have to be promoted to avoid the possibility of overloading the trap with soot.

It was assumed that trap loading, represented by the 21 percent change in $\sqrt{\Delta p}$, was sufficient to establish a regeneration balance temperature, or to observe what could be done to force a regeneration. The bus was run at 31 mph in top gear on the dynamometer to obtain 1260 rpm (intermediate speed). With a dynamometer load of 24 units (31 mph road load simulation), exhaust gas temperature to the trap (before turbocharger position) was about 280°C and trap Δp was 30 in H_2O. With a dynamometer load of 100 units, gas temperature to the trap increased to 350°C, and Δp was near 35 in. H_2O. Dynamometer load was increased to 200 units, and the temperature of the exhaust gases to the trap increased to 450°C. The trap Δp was 42 in. H_2O, and gas temperature out of the trap reached 430°C. Exhaust gases into the trap reached 475°C when the dynamometer load was increased to 225 units. At this condition, the Δp of the trap was about 43 in. H_2O, and appeared stable with a trap outlet temperature of 450°C. When the dynamometer load was increased to 275 units, the trap inlet temperature increased to 505°C, the trap outlet reached 525°C (exotherm noted), and the observed trap Δp began to decrease gradually. At full rack, the dynamometer load was increased to about 330 units and was varied slightly to control the engine speed at 1260 ± 10 rpm. Exhaust gases to the trap reached 540°C and the trap outlet temperature reached 560°C. Dynamometer load was gradually returned to 24 units to cool the trap; then the engine speed was reduced to idle.

Of the 40 minutes duration of this experiment, 13 minutes of it were conducted with the exhaust temperature to the trap in excess of 440°C (thought to be above the soot ignition temperature when catalysts were used on ceramic filters). After cool-down operation; trap Δp measured at 1500 rpm was 20 in. H_2O; on snap-idle, it was 33 in. H_2O; and at 50 mph, it was 48 in. H_2O. On CBD operation, the Δp was about 40 in. H_2O. These values of Δp indicated that regeneration had occurred, and that only a relatively small amount of particulate loading remained in the trap (similar to the level noted after brief operation on a new trap).

In preparation for experiments with Trap No. 2 located after the turbocharger, the bus was returned to operating conditions on the dynamometer to complete the regeneration of the trap. The load was increased to 250 units, then to 330 units, resulting in a trap inlet temperature range from 500 to 530°C. This condition was held for 14 minutes, then dynamometer load and exhaust gas temperatures were reduced. After cooling down, trap Δp at 1500 rpm measured 14 in. H_2O, and at snap-idle, it measured 23 in. H_2O (new trap Δp values were 11 and 19 in. H_2O, respectively).

Smoke had been monitored during the regeneration experiments. No puffs of smoke or smoke levels above three percent were noted. After the second run at 31 mph to complete regeneration, snap-idle checks resulted in smoke peaks near 4.5 percent opacity. The smoke peaks noted after regeneration were interpreted as an indication that the trap was essentially as "new", because similar smoke readings were obtained during initial operation with Trap No. 2. A borescope inspection of the ceramic filter substrates indicated that no damage occurred during regeneration on the dynamometer, and confirmed that the substrates were essentially clean.

The trap was considered to be "clean" and ready for experimentation after the turbocharger. The exhaust gas piping was rerouted to effectively place the trap in the after turbocharger position. With minimal engine operation for warm-up, "clean" trap Δp measured 18 in. H_2O at 1500 rpm, 45 in. H_2O on snap-idle, and 56 in. H_2O at 50 mph.

After a test sequence that included a bus cycle, CBD cycle, hot-idle, smoke, and W.O.T. accelerations to 50 mph, the trap Δp increased to 24 in. H_2O at 1500 rpm, 53 in. H_2O on snap-idle, and 62 in. H_2O at 50 mph. Peak values of trap Δp recorded during the initial run of the CBD cycle (on the "clean" trap) were 52 in. H_2O. After accumulating about 19 more miles with a repeat of the above test sequence, trap Δp increased to 26 in. H_2O at 1500 rpm, 59 in. H_2O on snap-idle, and 68 in. H_2O at 50 mph. An additional bus cycle and CBD cycle were run for additional trap loading, not followed by the usual 50 mph operation. Trap Δp measured 27 in. H_2O at 1500 rpm, 60 in. H_2O on snap-idle. Peak trap Δp during CBD operation was 63 in. H_2O.

The increase of Δp from 52 to 63 in. H_2O during CBD operation after accumulating about 33 miles (excluding the initial 5 miles before starting CBD operation) represented a 10 percent change in $\sqrt{\Delta p}$ with the trap after the turbocharger. This result compares to a 21 percent change in $\sqrt{\Delta p}$ after 44 miles with the trap before the turbocharger. Assuming that the $\sqrt{\Delta p}$ is proportional to the trap loading, a loading ratio was computed as the percent change in $\sqrt{\Delta p}$ per mile of cyclic operation. For the after turbocharger position the ratio was 0.30. For the before turbocharger position the ratio was 0.48. The higher ratio implies that Trap No. 2 loaded faster in the before turbocharger position than in the after turbocharger position.

Emissions determined with Trap No. 2 in the before and after turbocharger positions are given in Tables 26, 27, and 28 for the bus cycle, CBD cycle, and hot idle, respectively. Emission levels on the bus cycle and CBD cycle were determined without the muffler, just prior to testing with Trap No. 2.

Without the muffler, CO and particulate emissions were greater, and fuel economy worsened on the bus and CBD cycles compared to earlier runs. Not much change in hot-idle emissions was noted without the muffler. When Trap No. 2 was positioned before the turbocharger, bus cycle HC and CO levels were reduced to about one-third the baseline levels.

Emission levels of HC and CO also were reduced when Trap No. 2 was located after the turbocharger, but not to the extent noted with the before turbocharger position. The reductions in HC and CO were attributed to the use of an oxidation catalyst (formulation "A") applied to Trap No. 2. In the before turbocharger position, total particulate emissions on the bus cycle were reduced 88 percent from the baseline level from (1.6 to 0.2 g/km). Total particulate on the bus cycle was reduced by 94 percent with trap in the after turbocharger position. Emission levels from hot-idle with the trap in either position followed the same trends noted for the bus cycle and the CBD cycle. Over the relatively long idle period (15 minutes in "drive"), HC emissions increased slightly as the trap cooled (from 260°C to 170°C when after turbocharger, and from 300°C to 180°C when before turbocharger).

The difference in emissions with Trap No. 2 in different positions is likely because of different trap temperatures and varying effects on the engine air

TABLE 26. EMISSIONS FROM BUS 8296 ON THE CHASSIS BUS CYCLE

Bus Configuration	Emissions, g/km				Fuel Usage	
	HC	CO	NO_x	Part.	kg	km/kg
Average Baseline	1.55	5.96	12.05	1.63	2.58	1.80
Without Muffler	1.5	4.3	11	1.6	2.5	1.9
Trap No. 1 Before Turbo	2.5	9.5	11	0.3	2.3	2.0
Trap No. 1 After Turbo	1.7	7.0	10	0.3	2.4	2.0
Without Muffler	2.0	9.2	12	2.4	3.0	1.6
Trap No. 2 Before Turbo	0.6	1.8	13	0.2	3.0	1.6
Trap No. 2 After Turbo	0.4	4.8	13	0.1	3.0	1.6

TABLE 27. EMISSIONS FROM BUS 8296 ON THE CBD CYCLE

Bus Configuration	Emissions, g/km				Fuel Usage	
	HC	CO	NO_x	Part.	kg	km/kg
Average Baseline	1.5	5.1	13	1.6	1.9	1.7
Without Muffler	1.5	3.5	13	1.5	1.9	1.8
Trap No. 1 Before Turbo	1.2	14	12	0.4	1.9	1.8
Trap No. 1 After Turbo	1.4	6.3	11	0.3	1.8	1.8
Without Muffler	1.5	6.1	12	1.7	1.9	1.7
Trap No. 2 Before Turbo	0.2	1.2	11	0.2	1.9	1.7
Trap No. 2 After turbo	0.4	4.5	13	0.1	2.1	1.5

TABLE 28. EMISSIONS FROM BUS 8296 DURING IDLE

Bus Configuration	Emissions, g/test				Fuel Usage	
	HC	CO	NO_x	Part.	kg	km/kg
Average Baseline	5.5	7.5	27	2.0	0.9	--
Without Muffler	6.4	6.1	27	2.2	0.9	--
Trap No. 1 Before Turbo	5.9	8.1	27	0.2	0.9	--
Trap No. 1 After Turbo	4.6	6.2	25	0.3	0.9	--
Without Muffler	6.1	6.4	27	1.7	0.9	--
Trap No. 2 Before Turbo	1.8	0.5	29	0.2	0.9	--
Trap No. 2 After Turbo	3.5	3.7	27	0.1	0.9	--

scavenging over the cycles. In the after turbocharger position, trap inlet temperatures were lower, and trap Δp's were higher than noted for the before turbocharger position. Table 29 lists the peak values of various temperatures and pressures obtained on the CBD cycle operation with Trap No. 2 located before and after the turbocharger. When the trap was located after the turbocharger, air box pressures increased, engine exhaust temperatures decreased, and trap Δp increased (with assumed comparable loadings) compared to results when the trap was located before the turbocharger. With Trap No. 2 after the turbocharger, temperature to the turbocharger was 400°C. With Trap No. 2 before the turbocharger, temperature to the trap was 450°C.

Acceleration times run on the dynamometer for the bus without the muffler and with Trap No. 2 before and after the turbocharger are given in Table 30. The acceleration data without the muffler indicate that the bus was accelerating slightly faster than before. Data with Trap No. 2 indicate that acceleration performance with the trap located before the turbocharger may be slightly better than that obtained with the trap located after the turbocharger. Overall, of the data given in Table 30 indicate that the presence of the trap had a relatively minor effect on bus acceleration times.

The goal of reducing total particulate emissions by 70 percent was reached with Trap No. 2, which had particulate trapping efficiency of about 90 percent, but the ability of the trap to eliminate visible smoke (≤ 5 percent smoke opacity) was questionable. During initial test work, smoke opacities measured during initial accelerations were marginally below the visible smoke limit. As trap particulate loading increased (Δp increased), smoke opacities diminished to levels below 3 percent, and no smoke plume was visible.

Smoke opacities measured over the several test configurations are given in Table 31. Because snap-idle and stall are two extreme cases, smoke opacities measured during acceleration on CBD cycle operation were included for additional information. The smoke opacity values reported for acceleration are estimated to be representative of that which an observer might perceive as smoke from a bus pulling away from a stop.

After gathering necessary emission data with Trap No. 2 located after the turbocharger, trap Δp information indicated that the trap was loaded to the 10 percent level (based on the change in the $\sqrt{\Delta p}$). Regeneration on the chassis dynamometer was scheduled. With Trap No. 2 after the turbocharger, the bus was operated at 31 mph (1260 rpm) and the dynamometer load was increased from 25 to 200 units to determine regeneration requirements. With 200 load units, the temperature of exhaust in to the turbocharger reached 430°C, the trap inlet temperature reached 375°C, the temperature out of the trap reached 350°C, and trap Δp was 40 in. H_2O. The dynamometer load was increased to a maximum of approximately 320 units, where engine rpm was maintained at 1260 rpm with the engine at full rack. Trap Δp appeared to stabilize at 47 in. H_2O with the temperature of exhaust gases to the turbocharger at 550°C, trap inlet temperature was 475°C, and trap outlet temperature at 470°C. Stabilizing of the Δp with the trap near 470°C implies that the balance temperature of Trap No. 2 located after the turbocharger was 470°C. The time that exhaust gases to the turbocharger were above 440°C was 9 minutes. The length of time that trap inlet temperature was above 440°C was about 5 minutes.

TABLE 29. PEAK VALUES OF PARAMETERS MONITORED DURING CBD OPERATION OF BUS 8296

	Baseline	No Muffler 3/5/86	Trap No. 2 Before Turbo	Trap No. 2 After Turbo
Air Box Press., psig	14.1	13.8	9.3	13.0
Boost Press., psig	11.6	11.3	5.6	--
Turbo Inlet Temp, °C	345	410	322	440
Turbo Inlet Press., psig	13.8	11.8	7.1[b]	11.8
Trap Inlet Temp, °C	--	--	450	360
Trap Outlet Temp, °C	--	--	315	280
Trap Inlet Press., psig	--	--	8.7	2.5
Trap Δp, in H_2O	--	--	4.3	59

[a]clean trap - measured on CBD
[b]computed, trap inlet press. - Δp

TABLE 30. ACCELERATION TIMES OF BUS 8296 ON THE DYNAMOMETER WITH AN INERTIA OF 31,000 POUNDS

	Acceleration Time, Sec			
Speed Range, mph	0-10	0-20	0-40	0-50
Baseline	4.8	10.5	31.3	50
Without Muffler	4.3	9.8	33	54
Trap No. 1 Before	4.3	10.4	33	52
Trap No. 1 After	4.5	10.2	31	48
Without Muffler	4.0	9.5	29	48
Trap No. 2 Before	4.3	9.8	31	49
Trap No. 2 After	4.7	10.3	31	50

TABLE 31. SMOKE OPACITIES FROM BUS 8296

	Smoke Opacity, %			
Condition	Idle[a]	Snap Idle	Stall	Acceleration[b]
Baseline	0.8	35	4.2	29-37
Without Muffler	0.4	27	2.1	20-88
Trap No. 1 Before	0.3	2.0	1.2	1.2
Trap No. 1 After	0.3	2.0	2.3	0.5
Without Muffler	0.4	37	4.2	25-30
Trap No. 2 Before	0.3	1.5	0.6	2.0
Trap No. 2 After	0.3	1.0	0.3	1.0

[a]idle in neutral
[b]peak measured during CBD cycle

After cooling, the trap Δp measured 25 in. H_2O at 1500 rpm, and 58 in. H_2O on snap-idle. Only minimal regeneration was achieved, even though temperatures were relatively high. The trap inlet and outlet temperatures for the after turbocharger position of the trap were somewhat lower than for the before turbocharger position. Perhaps the trap loading was insufficient, or the high load condition was not held long enough, or gaseous emissions concentrations in conjunction with the other points were not conducive to regeneration.

Because substantial regeneration was not obtained with the trap located after the turbocharger, it was decided that additional experimentation should be pursued to promote high exhaust temperatures for regeneration. Hardware for six variables expected to cause higher exhaust temperatures or a higher level of CO was installed, including: 1) air box bleed, 2) blower bypass, 3) turbocharger boost bleed, 4) disablement of aftercooler 5) addition of EGR, 6) injection of methanol. The most desirable effect of any of the experiments was to increase the temperature of the ceramic substrate to an undefined temperature necessary to cause the collected carbon soot to be oxidized ($>500^{\circ}C$). The necessary temperature is dependent on catalyst coating, trap loading, gaseous emission concentrations, relative amounts of organics, etc.

If regeneration could be made to occur over the CBD cycle, the trap should never load to a level which would cause trap failure (critical loading) by overheating. The CBD cycle was chosen to assess the effect of the variables on promoting regeneration, because it was considered to represent typical bus operation and it represented a worst case for obtaining regeneration. The bus was operated over the CBD cycle on the chassis dynamometer until temperature and pressure data were repeatable.

Raw emissions of HC, CO, NO_x, CO_2, and O_2 in and out of Trap No. 2 located after the turbocharger were monitored. Smoke opacity was monitored using an in-line smokemeter in the exhaust pipe going to the CVS. Prior to experiments to promote regeneration of the catalyzed trap, Δp was 26 in. H_2O at 1500 rpm, 60 in. H_2O on snap-idle, and 72 in. H_2O at 50 mph. The data corresponding to repetitive CBD cycle operation are given in Table 32, under "Baseline." With trap substrate near $280^{\circ}C$, the catalyst showed some ability to reduce CO emissions. After baseline data were established, one valve was opened to provide air box bleed to atmosphere. Two valves, then three valves were opened for additional air box bleed to atmosphere over the CBD cycle. Corresponding temperature and pressure data are given in Table 32.

With one valve open for air box bleed, peak temperature to the trap increased by $55^{\circ}C$; and, the trap substrate temperature increased by approximately $30^{\circ}C$, with a slight increase in smoke (1% opacity) and a slight decrease in acceleration performance. Opening two valves for air box bleed increased the peak temperature to the trap (located after the turbocharger) to $470^{\circ}C$, and caused the trap substrate to reach $400^{\circ}C$. Three valves open for air box bleed increased the peak temperature to the trap to $520^{\circ}C$, and caused the trap substrate to reach $520^{\circ}C$ (measured 4.5 to 9.0 in. into the substrate). Unfortunately, the peak smoke level increased to 7.0 percent opacity with three valves of air box bleed, and the trap Δp did not decrease to indicate a net regeneration of the trap. In addition, acceleration performance with three valves open for air box bleed was substantially worsened.

TABLE 32. PARAMETERS DURING EXPERIMENTATION TO PROMOTE REGENERATION OF TRAP NO. 2

	Value by Configuration (CBD cycle all tests)						
Variable	Baseline	1 Valve Air Box Bleed	2 Valve Air Box Bleed	3 Valve Air Box Bleed	Baseline Repeat	1 Valve Blower Bypass	2 Valve Blower Bypass
Trap Δp, in H_2O	7-60	6-48	5-38	5-33	8-63	8-63	7-60
Temp. to Turbo, °C	250-435	270-490	310-550	350-610	240-440	260-460	275-475
Temp. to Trap, °C	220-360	240-410	270-470	300-520	200-360	230-385	240-400
Air Box, psi	0.7-11.7	0.7-8.4	0.6-6.0	0.5-4.2	0.9-11.1	0.8-10.4	0.6-9.6
Trap Out, psi	0.3-1.2	0.3-0.9	0.3-0.6	0.2-0.5	0.2-0.9	0.2-0.9	0.2-0.9
Substrate 1", °C	225-250	240-280	280-330	330-410	210-240	230-265	235-270
Substrate 4 1/2", °C	290	330	400	520	280	310	340
Substrate Out, °C	265-280	300-310	330-360	380-450	230-260	270-295	290-300
CO Before, %	0.01-0.23	0.01-0.33	0.02-0.41	0.04-0.45	0.01-0.25	0.01-0.31	0.02-0.35
After, %	0-0.07	0-0.07	0.01-0.09	0.01-0.11	0.0-0.07	0.0-0.10	0.0-0.14
HC Before, ppm	a	a	a	a	a	a	a
After, ppm	a	a	a	a	a	a	a
Accel 0-20, sec.	10.2	11.2	12.7	16.3	10.7	10.7	11.7
Smoke Peak, %	0.5	1.5	3.0	7.0	0.8	1.2	2.2
Turbo Boost, °C	55-90	55-80	52-70	52-63	60-90	60-90	60-90
Air Box Temp, °C	90-110	90-105	92-105	95-105	90-110	95-110	92-107

[a]no data
[b]valve open - no direct measurement of EGR
[c]methanol injected during CBD cycle accel and cruise
[d]HC instrument over-ranged, no increase in CO noted

TABLE 32 (CONT'D). PARAMETERS DURING EXPERIMENTATION TO PROMOTE REGENERATION OF TRAP NO. 2

	Value by Configuration (CBC cycle all tests)					
Variable	3 Valve Blower Bypass	Baseline Repeat	After Cooler Off	Filtered EGR, [b]	Methanol Injection, [c]	Baseline After Regeneration
Trap Δp, in H_2O	8-60	10-72	10-73	11-73	11-77	5-49
Temp. to Turbo, °C	290-500	250-445	250-450	265-460	250-450	220-420
Temp. to Trap, °C	250-425	220-370	220-380	230-390	220-380	200-340
Air Box, psi	0.6-8.8	0.9-11.0	0.9-11.0	0.9-10.5	0.9-11.0	0.9-11.2
Trap Out, psi	0.2-0.8	0.2-1.0	0.2-1.0	0.2-0.9	0.2-1.0	0.3-0.9
Substrate 1", °C	250-290	210-250	220-260	220-270	220-260	190-220
Substrate 4 1/2", °C	350	285	290	310	300	260
Substrate Out, °C	320-330	260-280	270-280	285-295	275-285	235-250
CO Before, %	0.02-0.38	0.01-0.27	0.01-0.27	0.01-0.31	0.01-0.27	0.01-0.27
After, %	0.0-0.09	0.01-0.12	0.01-0.12	0.0-0.09	0.01-0.09	a
HC Before, ppm	a	60-400	a	a	400[d]	a
After, ppm	a	20-80	a	a	400[d]	a
Accel 0-20, sec.	12.2	11.7	11.2	11.2	11.2	10.2
Smoke Peak, %	4.5	1.0	1.0	1.5	1.0	a
Turbo Boost, °C	62-88	60-90	60-90	70-100	60-90	45-75
Air Box Temp, °C	93-108	92-110	95-112	100-117	92-110	85-102

[a]no data
[b]valve open - no direct measurement of EGR
[c]methanol injected during CBD cycle accel. and cruise
[d]HC instrument over-ranged, no increase in CO noted

Prior to evaluating other variables, baseline CBD operation was re-established. The next variable tried to promote regeneration was blower bypass in three increments, also controlled by three valves. One valve, then two, then three valves were opened during CBD operation. Corresponding data are given in Table 32, and show that three valves open for blower bypass caused the peak temperature to the trap to increase to 425°C. This configuration also caused the temperature of the trap substrate to increase to 350°C, while a peak smoke level of about 4.5 percent opacity was observed. These results could likely be duplicated using air box bleed equivalent to 1 1/2 valves open, which would probably result in lower smoke emissions.

Following another repeat of baseline CBD operation, water flow through the aftercooler was interrupted by closing a valve added for that purpose, to study the effect of removing the aftercooler. No significant change in the observed data could be attributed to the interruption of water flow through the after-cooler, because no change in air box temperature was noted. Based on the relatively low temperatures ($\leq$90°C) of boost air during CBD operation, blocking the aftercooler appeared to have little effect on raising the charge air temperature and hence, exhaust temperature. It is likely that water stored in the aftercooler attenuated the expected effect.

The use of particulate-trap-filtered EGR introduced into the intake of the turbocharger was expected to increase the air box temperature and reduce air/fuel ratios substantially. Use of EGR was also expected to substantially influence all the emissions from the engine by reducing the scavenging air and available oxygen. A small amount of EGR was introduced into the intake air system by opening a one-inch gate valve. Only a small amount of EGR was introduced, and its influence on engine parameters was minor. Further experiments using greater quantities of EGR were planned.

Methanol injected into the hot exhaust stream was expected to dissociate into hydrogen and carbon monoxide; which, in turn, were expected to be oxidized in the catalyzed trap, creating additional heat needed to achieve regeneration. Because the catalyst on Trap No. 2 was somewhat active in reducing CO levels, methanol was injected in front of the turbocharger during CBD operation. Approximately 30 ml of methanol was injected over each of two consecutive CBD cycles, with anticipation of about a 50°C exotherm. No increase in temperature was observed. In fact, no increase in CO levels (anticipated from dissociation) occurred. Only high levels of HC (unburned methanol) were noted.

This preliminary round of experiments with the trap located after the turbocharger demonstrated that air box bleed was effective in raising the exhaust system temperature. It should be noted that the temperature to the trap increased slightly (from 360 to 380°C) because of a slight increase in engine backpressure as Trap No. 2 loaded (peak Δp increased from 60 to 77 in. H_2O) during these experiments. Based on this observation, experiments with variation in engine backpressure also were planned.

The Δp of trap No. 2 reached 77 in. H_2O during CBD operation. The percent of change in $\sqrt{\Delta p}$, (7.21 initially to 8.77) indicated the trap was loaded to a 22 percent level with the trap after the turbocharger. The bus was operated at 31 mph on the dynamometer for regeneration. Dynamometer load was increased to 240 units so that the engine was at 1260 rpm and full load. The temperature and pressure data obtained at this condition are given in Table 33 under "Base 1st Run." Based on previous experiments, one valve for air box bleed was opened to increase trap temperatures. Temperatures increased rapidly so that after 1.5 minutes the valve was throttled back to about half-open. This action stabilized the temperatures and pressures to the levels given in Table 33. Trap Δp was noticeably reduced when the valve was finally closed. After partial trap regeneration, the dynamometer load had to be increased to 280 units to hold engine speed to 1260 rpm at 31 mph. The time during which the exhaust gases to the turbocharger exceeded 440°C was 9 minutes, and the length of time the trap inlet temperature exceeded 440°C was 8 minutes. After trap cool-down, the trap Δp measured 20 in. H_2O at 1500 rpm and 61 in. H_2O during snap-idle. These levels of Δp correspond to a 10 percent level of trap particulate loading.

TABLE 33. PARAMETERS DURING REGENERATION OF TRAP NO. 2 POSITIONED AFTER THE TURBOCHARGER

	Value by Configuration at 31 mph Steady-State					
Variable	Base 1st Run	1 Valve Air Box Bleed	Throttled Air Box Bleed	Base 2nd Run	1 Valve Air Box Bleed	Base After
Trap Δp, in. H_2O	76	53	53	53	30	37
Temp to Turbo, °C	560	640	620	550	640	565
Temp to Trap, °C	490	560	540	470	560	495
Air Box, psi	7.95	5.70	6.60	7.50	5.80	7.95
Trap Out, psi	0.75	0.60	0.66	0.66	0.66	0.90
Substrate 1", °C	410	480	480	445	483	b
Substrate 4 1/2", °C	490	590	580	520	605	b
Substrate Out, °C	450	540	585[a]	400	625	b
CO Before, %	0.19	0.32	0.25	0.19	0.28	0.15
HC Before, ppm	48	32	34	a	a	38
Turbo Boost °C	92	82	88	90	92	105
Air Box Temp°C	105	110	110	105	110	110

[a]peak
[b]falling

The bus was brought back up to 31 mph and the dynamometer load was increased to obtain an engine condition of 1260 rpm at full load to complete the trap regeneration. After about 1.5 minutes, parameters reached the levels given in Table 33 under "Base 2nd Run." Then one valve for air box bleed was opened. The valve was left open for 7 minutes. Temperature to the turbocharger reached 640°C, temperature at the trap inlet reached 560°C, and temperature out of the trap reached 625°C. The valve was closed, and temperatures declined to the levels given in Table 33 under "Base After." Exhaust gas temperatures exceeded 440°C for 13 minutes, and temperature to the trap exceeded 440°C for 12 1/2 minutes. After cooling, trap Δp measured 18 in. H_2O at 1500 rpm and 41 in. H_2O at snap-idle, indicating that the trap was essentially clean. Temperature and pressure data for CBD operation with a clean trap are given in Table 32 for reference ("Baseline After Regeneration").

Even though regeneration could be obtained with the engine at 1260 rpm and full load, and with one valve open for air box bleed, further experiments to promote regeneration were run. Engine air flow was reduced by opening three valves of air box bleed during the idle phase of the CBD cycle. Reducing the air box pressure from 0.9 to 0.6 psi during idle increased the temperature to the turbocharger by 10°C, but it made no noticeable difference to the overall trap temperature. Three open valves of air box bleed during a 20 mph cruise had little influence (20°C increase) on trap temperature or emissions. At 31 mph cruise, the trap temperature was increased by 20°C with minimal effect on emissions. For another variation, the three valves for air box bleed were closed during the acceleration to 20 mph, on the CBD cycle; then opened for the 20 mph cruise phase, the deceleration phase, and the idle phase. No significant change in trap temperature (only 10°C net increase) was noted.

Experiments conducted with three valves open for blower bypass resulted in approximately a 15°C increase in overall temperature of the trap. Additional experiments with turbocharger boost venting were run. Air box bleed appeared to be most effective in achieving higher temperatures with increased CO and smoke (to be trapped as particulate). Additional experiments with injection of methanol had no noticeable effect on trap temperature and no increase in CO observed, but they did cause HC levels to exceed the 400 ppm range. Variation of air box bleed, blower bypass, and turbocharger boost bleed were tried during steady-state operation as well as CBD operation without obtaining significantly greater temperature increases than already noted during similar experiments.

To pursue experiments with EGR, an exhaust damper was installed after the trap to backpressure the system and force more EGR into the engine air intake. The exhaust damper and the one-inch EGR line with a valve are shown in Figure 19. The EGR line pressure was monitored with no flow, and it varied from -3.5 to -0.3 in. H_2O gage during CBD operation. The valve was opened for EGR, and the line pressure varied from -1.5 to -0.2 in. H_2O during CBD operation. Although no noticeable change in trap temperature was observed, peak NO_x emissions declined from 380 to 300 ppm, and smoke emissions increased from 0.7 to 1.0 percent opacity. The backpressure damper was closed to cause the EGR line pressure to vary from -0.5 to +1.0 in. H_2O during CBD operation. A 15°C increase in trap temperature was noted, along with an increase in peak HC concentration from 188 to 256 ppm, an increase in peak CO from 0.30 to 0.35 percent, and an increase in peak smoke to 2.5 percent opacity. Peak NO_x emission was reduced to 270 ppm.

Additional experiments with EGR included operating the backpressure damper such that the EGR line pressure was +3.0 in. H_2O only during the idle and deceleration phases of CBD operation. These and other variations of EGR flow resulted in after-trap smoke emissions in excess of 5 percent opacity, without creating noticeable temperature increases in the trap. Experimentation with EGR was discontinued. The trap was regenerated using a

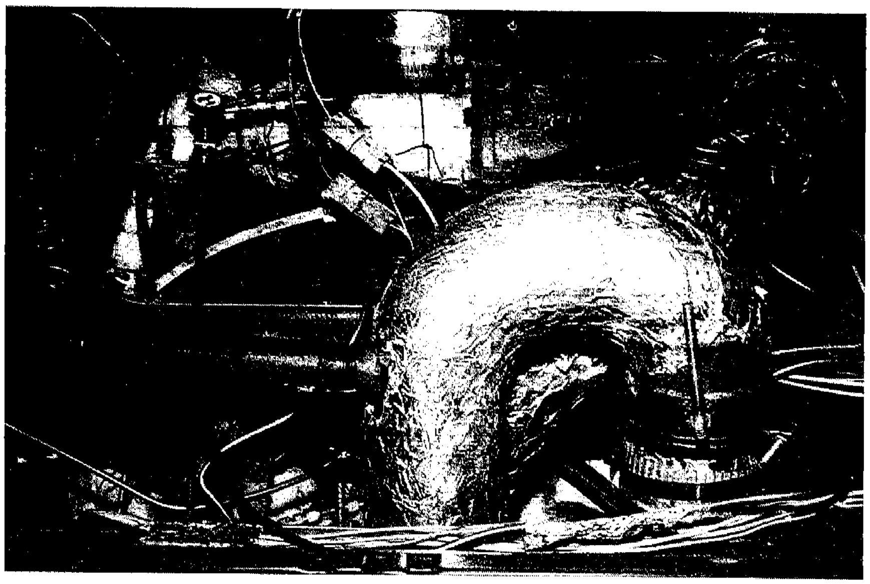

FIGURE 19. PIPING ARRANGEMENTS FOR EXPERIMENTING WITH EGR ALONG WITH 1/8 LINES USED TO INTRODUCE METHANOL BEFORE THE TURBOCHARGER

31 mph steady-state run with increased load (1260 rpm/full load) and one valve open for air box bleed. After cooling, the trap Δ p measured 18 in. H_2O at 1500 rpm and 42 in. H_2O during snap-idle (essentially clean-trap levels).

Exhaust piping was rerouted to place the clean Trap No. 2 before the turbocharger. Trap Δ p measured 17 in. H_2O at 1500 rpm, 26 in. H_2O on the snap-idle, and 42 in. H_2O at 50 mph. After minimal operation, the trap Δp on snap-idle increased to 33 in. H_2O. The bus was operated over repetitive CBD cycles to establish temperature, pressure, and emission information for baseline. Repetitive CBD operation was continued to investigate the effect of experiments to promote trap regeneration with the trap located before the turbocharger. Results from these experiments are given in Table 34. During "Baseline" operation with the trap positioned before the turbocharger, the peak temperature to the trap was 470°C (compared to 340°C for the after turbocharger position with a clean trap). Even though the before turbocharger trap inlet temperature was 130°C higher, the temperatures of the ceramic substrates were only about 60°C higher. In addition, the 0 to 20 mph acceleration time with the trap before the turbocharger was 1.5 seconds longer than when the trap was located after the turbocharger.

Experiments to promote regeneration during CBD operation with Trap No. 2 located before the turbocharger began with varying degrees of air box bleed. After stabilizing temperatures and pressures with one valve open for air box bleed, a second valve was opened, then a third. Resulting data are given in Table 34 under corresponding headings. As the peak air box pressure was reduced from 8.0 to 4.6 psi by opening the three air box valves to atmosphere, peak trap inlet temperatures increased from 470°C to 575°C. It should be noted that with three valves of air box bleed opened, the oxygen concentration was never reduced below 6 percent. In addition, the temperature of the ceramic substrate increased from about 320°C to about 420°C, but smoke emissions increased from about 1.2 to 4.8 percent opacity. When the three valves were closed, prior to a CBD cycle, the smoke over the next CBD cycle momentarily reached 8 percent opacity, then dropped to normal. It is assumed that this phenomenon was a function of increased gas velocities blowing off loose particulate from the EX-66 substrate of Trap No. 2.

The three air box bleed valves were closed and trap temperatures were allowed to stabilize. Additional experiments were conducted during CBD operation with all three air box bleed valves opened only during idle and decelerations phases. No noticeable increase in the temperature of the trap was observed. The effects of air box bleed during idle and 20 mph steady-state operation were also negligible. During 31 mph cruise conditions, three open valves of air box bleed produced about a 30°C increase in trap temperature, with little change in HC, CO, NO_x, or smoke emissions.

Normal CBD operation was resumed, and readings are given in Table 34 under "Baseline Repeat." Trap Δp for CBD operation had increased from 38 to 50 in. H_2O during experimentation with methods to promote regeneration. Three valves of blower bypass were opened, resulting in a 40°C increase in the peak inlet temperature to the trap and a general trap temperature increase of 40°C. Peak smoke emission increased to about 3.5 percent opacity. As with the after turbocharger experience, the degree of blower bypass used here had about the same effect as when one valve of air box bleed was used.

TABLE 34. PARAMETERS DURING EXPERIMENTATION TO PROMOTE REGENERATION OF TRAP NO. 2 BEFORE THE TURBOCHARGER

	Value by Configuration (CBD cycle all tests)								
Variable	Baseline	1 Valve Air Box Bleed	2 Valve Air Box Bleed	3 Valve Air box Bleed	Baseline Repeat	3 Valve Blower Bypass	3 Valve Turbo Boost Vent	Baseline Repeat	2 Valve Air box Bleed + Methanol[c]
Trap Δp, in H_2O	6-38	6-36	6-34	6-32	9-50	8-47	10-47	9-61	11-54
Temp to Turbo[a], °C	300-310	320-330	355-370	400-420	310-320	350-360	335-345	310-320	385-395
Temp to Trap, °C	210-470	220-500	245-540	260-575	210-480	235-520	230-525	210-480	250-550
Air box, psi	1.0-8.00	0.9-6.45	0.8-5.40	0.8-4.65	0.9-7.80	0.8-6.60	0.9-6.20	1.0-8.55	0.9-5.85
Trap Out, psi	0.9-7.20	0.8-5.70	0.6-5.10	0.6-4.20	0.8-6.90	0.4-5.70	0.4-5.25	0.7-7.20	0.6-4.80
Substrate 1", °C	230-315	240-325	260-360	280-340	220-320	240-350	230-350	220-350	250-390
Substrate 4 1/2", °C	315-325	325-335	385-400	445-455	335-345	370-390	360-370	b	405-415
Substrate Out, °C	295-305	315-325	345-360	390-410	305-310	340-350	325-330	305-315	380-385
CO Before, %	0.01-0.30	0.01-0.33	0.01-0.38	0.01-0.41	0.02-0.31	0.02-0.39	0.02-0.33	0.01-0.30	0.01-0.38
After, %	0.01-0.17	0.01-0.20	0.01-0.16	0.01-0.16	b	0.02-0.14	b	0.0-0.11	0.01-0.07
HC Before, ppm	60-150	60-150	60-250	60- 400	40-180	60-340	60-180	70-140	80-300
After, ppm	30-70	20-80	20-90	20-320	b	20-212	b	30-50	25-170
Accel 0-20, sec	11.7	12.7	13.5	14.2	11.7	12.7	11.7	11.4	12.7
Smoke Peak, %	1.7	2.2	3.3	4.8	1.3	3.5	2.0	1.0	3.2
Turbo Boost, °C	40-50	40-50	40-50	40-50	40-55	40-55	40-50	40-55	35-45
Air Box Temp, °C	82-100	85-100	85-100	85-100	85-100	85-100	85-100	85-100	b

[a]assumed to be equal to trap out
[b]no data
[c]methanol was added - but no response was attributed to methanol

After some additional runs with all valves closed, CBD operation with three valves venting turbocharger boost air was conducted. Peak temperature to the trap reached 525°C, 45°C above baseline repeat. Trap temperatures were generally 20°C higher than baseline. Acceleration performance was similar to baseline, and only a slight increase in peak smoke was noted.

Injection of methanol was still of prime interest, because it seemingly offered the potential to rapidly increase the temperature of the trap through oxidation via the catalyst coating. Although previous experiments indicated no change in trap temperature due to methanol injection, those experiments were conducted with the trap below 350°C. It was assumed that since the catalyst was oxidizing HC and CO, it would also readily oxidize the methanol introduced into the exhaust stream.

It was decided that methanol injection would be tried again, but with the trap above 350°C. A baseline repeat on CBD operation was established, then two valves of air box bleed were used to raise the trap temperature to about 400°C. Fifty milliliters of methanol were injected, within about five seconds, into the exhaust piping leading to the trap. The sequence was repeated over various portions of CBD operation. No influence on trap temperature was noted. Only exhaust HC concentrations increased, exceeding the 400 ppm range.

No further experiments to promote regeneration were scheduled because varying degrees of air box bleed appeared to be adequate to increase trap temperature. During normal CBD operation that followed these experiments, the trap Δp measured 64 in. H_2O. This level represented a trap loading of 27 percent. The trap had been regenerated when loaded to a level near 21 percent during earlier work.

It was decided that road work should commence, and that the trap should be left in the before turbocharger position because lower temperatures encountered with use of the after turbocharger position made it even more difficult to initiate regeneration. The trap was not regenerated prior to road work because it was assumed that a certain level of particulate loading had to be present in the trap before a significant trap regeneration would take place.

The bus was driven to the road course, and noise measurements were made during W.O.T. pull-away operation. The results from this noise test sequence, along with others, are given in Table 35. The noise levels at all three positions were lower than those obtained at baseline. Following completion of noise testing, the bus was operated for acceleration performance prior to starting the road route. Acceleration times, given in Table 36, indicate a slight deterioration in acceleration performance with Trap No. 2 (loaded to about the 27 percent level with particulate) compared to baseline. The ambient conditions corresponding to road test work are given in Table 37.

The bus was operated in a normal manner during the first run of the road route to see if any self-regeneration would occur. Generally, higher temperature exhaust gases and trap temperatures were noted during road work with Trap No. 2 than had been noted with Trap No. 1 in the before turbocharger position. It is likely that a portion of the higher temperatures

TABLE 35. ACCELERATION NOISE LEVELS FROM BUS 8296 ON THE ROAD

		Noise Level, db, by Configuration		
Position[a]	Baseline	Trap No. 1 Before Turbo	Trap No. 1 After Turbo	Trap No. 2 Before Turbo
1	97[b]	94	96	92
2	97	95	94	93
3	100	96	95	97

[a]Position 1 is 10 ft. behind bus, position 2 right side of bus during drive-by, and position 3 is left side bus during drive-by.
[b]had been recorded as 94 in the "as received" condition

TABLE 36. ACCELERATION TIMES FROM BUS 8296 ON THE ROAD (NO BALLAST ADDED)[a]

		Time, Sec, by Configuration			
MPH	Baseline	Trap No. 1 Before Turbo	Trap No. 1 After Turbo	Trap No. 2 Before Turbo[b]	Trap No. 2 After Turbo[c]
0-10	3.8	3.9	4.0	4.1	4.3
0-20	8.4	9.0	8.8	9.4	10
0-40	25	29	27	31	34

[a]bus loaded with 800 lb, air conditioning off
[b]from road route Run 1
[c]from road route Run 4

TABLE 37. AMBIENT CONDITIONS DURING ROAD EVALUATION

Test Configuration	Temperature Dry, °F	Temperature Wet, °F	Barometer in Hg	Test Date
Baseline	78	72	29.26	11/8/85
Trap No. 1 After	57	50	29.42	2/13/86
Trap No. 1 Before	72	60	29.25	2/14/86
Trap No. 2 Before	78	66	29.38	4/24/86

noted were the result of a higher ambient temperature, combined with reduced engine breathing due to the higher backpressure offered by the partially loaded trap.

Over the approximate 10-mile road course, the trap Δp for snap-idle increased slightly to 75 in. H_2O, with trap-out temperature at 260°C. Temperatures and pressures encountered during the road work are given in Table 38. The highest temperature at the trap inlet (520°C) was observed during stop-to-stop operation. The highest temperature out of the trap was obtained just after cresting the hill on the hill climb phase of the road route. The temperature of exhaust gas in to the trap was somewhat related to the temperature of the trap itself. As the trap temperature increases, the trap restriction increases. This restriction reduces the ability of the engine to breathe, increasing cylinder-out exhaust temperatures and increasing the temperature to the trap.

TABLE 38. PARAMETERS FROM RUN 1 OF ROAD WORK FOR BUS 8296 WITH TRAP NO. 2 BEFORE TURBO

	Value by Operating Condition				
Parameter	Idle	Stop to Stop	Accel @ 20 mph	Accel @ 40 mph	Hill Climb (Max.)
Air Box Press, psig	1	1-11	10.2	11.1	22
Boost Press, psig	0.6	0.7-7.2	6.2	6.9	12.0
Temp. to Turbo, °C	300	330-370	260	265	420
Press. to Turbo, psig[a]	0.5[a]	0.4-7.6[a]	7.3[a]	7.9[a]	16[a]
Temp. to Trap, °C	230	220-520	485	510	500
Temp. from Trap, °C	300	330-370	260	265	420
Press. to Trap, psig	0.9	1-11	10.2	11.1	20
Trap Δp, in. H_2O	12	15-93	79	87	100

[a]calculated from "pressure to trap" minus "trap Δp"

A second run of the road route was made to see if the trap Δp would stabilize or increase. In general, the temperatures and pressures encountered during the second run were similar to the first but slightly higher. Prior to starting the second run, a snap-idle Δp check indicated 95 in. H_2O with trap-out temperature at 300°C. After completing the second route, the trap Δp for snap-idle was 89 in. H_2O with the trap out temperature at 290°C. Lower snap-idle Δp readings at comparable trap temperatures imply that a net regeneration occurred over the second running of the road route. A subtle regeneration may have occurred during operation for acceleration performance, during acceleration <u>to</u>, or <u>on</u> the hill climb phase of the road route.

The objective was to achieve regeneration frequently enough during road operation so that the trap would not load to a potentially damaging level if a regeneration suddenly occurred. To pursue this goal, a third run of the road route was made with one valve open for air box bleed. The maximum temperature at the inlet to Trap No. 2 during the hill climb phase was 550°C, and the highest trap out temperature was 475°C. The maximum temperatures to and from the trap during stop-to-stop operation were 550°C and 410°C, respectively. With the air box bleed valve closed after completing the run, snap-idle Δp measured 84 in. H_2O. This value represented another decrease in overall trap loading.

It was anticipated that when trap loading reached a certain level, the engine could be upset using air box bleed to cause a significant regeneration. After regeneration, engine upset could be eliminated until needed again because of high trap loading.

In an effort to achieve a significant regeneration over the road route, an exhaust damper was set to increase the backpressure. Increased backpressure was expected to increase the temperature at the trap inlet. Problems with damper vibration caused the experiment to be abandoned.

It was decided that a fourth run would be made with two valves of air box bleed. Temperature and pressure data obtained on the fourth run are given in Table 39. Maximum temperatures into and out of the trap on the hill climb phase were 600 and 530°C, respectively. Maximum temperatures into and out of the trap on the stop-to-stop portion were 575 and 440°C, respectively. It was also noted that higher temperatures were encountered on the road, during the stop-to-stop phase, than those noted during chassis dynamometer operation on the CBD cycle. The reason for this difference was that the CBD cycle acceleration was terminated at 20 mph; whereas, during stop-to-stop road work, the bus sometimes reached near 40 mph and encountered sections of inclined roadway. A check of trap Δp at idle, just after the hill climb and cruise phases, indicated that some regeneration had occurred (13 in. H_2O during the second run versus 8 in. H_2O during the fourth run).

TABLE 39. PARAMETERS FROM RUN 4 OF ROAD WORK FOR BUS 8296 WITH TRAP NO. 2 BEFORE TURBO (WITH 2 VALVE AIR BOX BLEED)

	Value by Operating Condition				
Parameter	Idle	Stop to Stop	Accel @ 20 mph[b]	Accel @ 40 mph[b]	Hill Climb (Max.)
Air Box Press, psig	0.7	1-8.1	4.2	5.4	15.3
Boost Press, psig	0.4	0.3-4.5	0.8	1.2	8.4
Temp. to Turbo, °C	390	410-440	225	260	530
Press. to Turbo, psig[a]	0.4[a]	0-1.9[a]	2.2[a]	2.7[a]	10.2[a]
Temp. to Trap, °C	260	250-575	485	585	600
Temp. from Trap, °C	390	410-440	225	260	530
Press. to Trap, psig	0.7	0.3-4.5	4.2	5.4	13.8
Trap Δp, in. H_2O	7	10-71	53	72	97

[a]calculated from "pressure to trap" minus "trap Δp"
[b]data from acceleration during hill climb phase of Run 4 of road route

During return to the start of the road route, it was decided to interrupt the road work. The trap substrate was at 580°C, and trap outlet temperature was 470°C. The bus was idled in neutral for approximately 40 seconds before the engine was turned off. Trap inlet temperature was 280°C, trap substrate temperature was 530°C, and trap outlet temperature was 500°C. It was assumed that the majority of the trap accumulation had been oxidized by the high temperatures reached during the previous road work. After the engine was off for 12 minutes, trap inlet temperature was 240°C, trap outlet temperature was 220°C, but the substrate was at 530°C. Approval was given to start the engine. The engine was cranked for about one second but did not start. Then it was cranked again, but this time, the two valves for air box bleed were closed after another second of cranking, and the engine started. After idling for a few seconds, the two air box bleed valves were opened. The bus was put into gear and pulled out to return to the end/start point of the road route, when it was noted that the trap outlet temperature peaked at 630°C shortly after start-up. At the end/start point of the road route, a snap-idle conducted with air box bleed valves closed showed a trap Δp of 39 in. H_2O (snap-idle Δp for a clean trap before the turbocharger was 19 in. H_2O). Black smoke was emitted during the snap-idle. It was hypothesized that this smoke was because of an extremely clean trap, and not due to a damaged ceramic substrate.

A fifth run of the road route was conducted. The maximum temperature into the trap was 490°C during the stop-to-stop phase. The maximum temperature from the trap was 380°C, observed during the hill climb phase of the road route. The snap-idle Δp at the end of the road route was 48 in. H_2O, indicating that the trap was loading. Smoke emission was also somewhat lower during the snap-idle, but still easily visible.

A sixth run was made to see if trap loading would continue. At the end of that run, snap-idle Δp registered 49 in. H_2O. Smoke emissions during snap-idle appeared worse. Road work was discontinued. A borescope inspection of the outlet faces of the ceramic trap substrates was made. About four blackened spots, each 1 to 2 in. in diameter, were visible on each outlet face, confirming that the ceramic substrates were damaged.

It is difficult to say when the failure occurred, if it all occurred at the same time, or if it occurred through aggravation of weak spots introduced during previous regeneration experiments. No chase car was in use to observe exactly when visible smoke emissions first occurred during the road work. It is assumed that the damage occurred during the hill climb phase or during restart after the 12-minute engine shut-down. Highest temperatures were noted after the engine restart episode. It is assumed that unburned diesel fuel reached the hot, catalyzed ceramic trap; however, other failure modes may have occurred.

A review of the temperature data recorded during the engine restart episode showed the temperature at the trap outlet was 220°C; increasing to 240°C with the initial one second of engine cranking. During the period which included the second engine cranking episode, air box bleed valve closure for start-up, and drive-away, the temperature out of the trap reached 415°C. Over the next ten seconds, during acceleration of the bus, the temperature out of the trap reached 600°C. Eighteen seconds later, the temperature peaked at 630°C, then fell off. Temperature of the ceramic filter substrate (measured 4.5 inches in from the face) was 530°C before restart. During the time from initial cranking to engine start-up, it changed little (532°C). During acceleration of the bus, the temperature fell off rapidly and linearly, at a rate of 3°C/second. Meanwhile, the trap outlet temperature peaked at 630°C, yet the trap substrate (measured 4.5 inches in from the face) had decreased to 435°C. After 61 seconds from engine restart, the trap substrate was at 360°C, and the trap outlet was at 480°C. Switching to monitor trap substrate outlet temperatures indicated 620°C for the left substrate and 520°C for the right substrate. The actual failure mode of the trap assembly is unknown, but it is assumed that localized melting of several channels occurred. It was puzzling that a temperature spike or increase was not noted inside the ceramic substrate, while the outlet of the substrate apparently reached very high temperatures. It may be that accumulations of particulate located downstream of 4.5 in. point inside the trap were rapidly oxidized during engine start-up, creating high-temperature damage to the ceramic filter substrates.

Replacement catalyzed ceramics were ordered to rebuild Trap No. 2. To reduce the lead time, replacement units were scheduled to be constructed of Corning EX-47 substrate coated with the same catalyst formulation originally used for Trap No. 2. Substitution of EX-47 for EX-66 was not expected to affect catalyst operation, but was expected to yield a more durable trap with an even better particulate trapping efficiency.

D. Trap No. 3

Trap No. 3 was installed in place of Trap No. 2, which was damaged during over-the-road experimentation. Exhaust gases were routed around the trap so that the bus could be positioned on the chassis dynamometer. After completing emission measurements without a muffler, the exhaust was routed into Trap No. 3 in the before turbocharger position. Replicate runs over the bus cycle, CBD, and hot-idle were made for primary emissions measurements. The average values of these emission measurements are given in Tables 40, 41, and 42 along with data obtained during other runs. Smoke emissions and acceleration performance data are given in Table 43 and 44. Additional chassis cycles were run to increase the trap loading, then regeneration was performed on the chassis dynamometer using a steady-state speed of 31 mph (engine speed of approximately 1260 rpm). Regeneration was evident when full-load engine operation was maintained during the 31 mph steady-state condition. This condition caused the trap inlet temperature to reach 540°C and the trap substrate to reach 555°C.

The exhaust was routed through Trap No. 3, after the turbocharger, and emissions were measured for bus cycle, CBD, and hot-idle operation. Emissions and performance data are given in Tables 40 through 44. Additional cycles were run to increase the trap loading. As before, a regeneration was attempted by running 31 mph with full load, but no regeneration on the basis of reduced trap Δp, was observed with the trap located after the turbocharger. The trap reached a maximum temperature of 480°C. Another attempt at regeneration was made with two valves open for air box bleed. At 31 mph with full load and engine upset, regeneration was observed with the trap inlet at 570°C and the trap substrate at 600°C. Another experiment to promote regeneration involved increasing the engine backpressure. The pressure after the turbocharger

TABLE 40. EMISSIONS FROM BUS 8296 ON THE CHASSIS BUS CYCLE

Bus Configuration	Emissions, g/km HC	CO	NO_x	Part.	Fuel Usage kg	km/kg
Average Baseline	1.55	5.96	12.05	1.63	2.58	1.80
Without Muffler	1.5	4.3	11	1.6	2.5	1.9
Trap No. 1 Before Turbo	2.5	9.5	11	0.3	2.3	2.0
Trap No. 1 After Turbo	1.7	7.0	10	0.3	2.4	2.0
Without Muffler	2.0	9.2	12	2.4	3.0	1.6
Trap No. 2 Before Turbo	0.6	1.8	13	0.2	3.0	1.6
Trap No. 2 After Turbo	0.4	4.8	13	0.1	3.0	1.6
Without Muffler	2.1	8.4	12	2.1	2.5	1.9
Trap No. 3 Before Turbo	1.4	19	10	0.3	2.6	1.8
Trap No. 3 After Turbo	1.6	11	11	0.3	2.7	1.7
Without Muffler	2.0	12	13	2.9	3.0	1.6
Trap No. 4 Before Turbo	1.9	26	12	0.2	3.0	1.6

TABLE 41. EMISSIONS FROM BUS 8296 ON THE CBD CYCLE

Bus Configuration	Emissions, g/km HC	CO	NO_x	Part.	Fuel Usage kg	km/kg
Average Baseline	1.5	5.1	13	1.6	1.9	1.7
Without Muffler	1.5	3.5	13	1.5	1.9	1.8
Trap No. 1 Before Turbo	1.2	14	12	0.4	1.9	1.8
Trap No. 1 After Turbo	1.4	6.3	11	0.3	1.8	1.8
Without Muffler	1.5	6.1	12	1.7	1.9	1.7
Trap No. 2 Before Turbo	0.2	1.2	11	0.2	1.9	1.7
Trap No. 2 After Turbo	0.4	4.5	13	0.1	2.1	1.5
Without Muffler	1.4	7.7	12	1.9	1.8	1.8
Trap No. 3 Before Turbo	1.0	24	10	0.2	1.9	1.7
Trap No. 3 After Turbo	1.2	8.7	11	0.3	2.0	1.7
Without Muffler	1.4	8.8	12	2.3	1.8	1.8
Trap No. 4 Before Turbo	0.9	29	10	0.3	1.8	1.8

TABLE 42. EMISSIONS FROM BUS 8296 AT IDLE

Bus Configuration	Emissions, g/test HC	CO	NO_x	Part.	Fuel Usage kg	km/kg
Average Baseline	5.5	7.5	27	2.0	0.9	--
Without Muffler	6.4	6.1	27	2.2	0.9	--
Trap No. 1 Before Turbo	5.9	8.1	27	0.2	0.9	--
Trap No. 1 After Turbo	4.6	6.2	25	0.3	0.9	--
Without Muffler	6.1	6.4	27	1.7	0.9	--
Trap No. 2 Before Turbo	1.8	0.5	29	0.2	0.9	--
Trap No. 2 After Turbo	3.5	3.7	27	0.1	0.9	--
Without Muffler	5.5	6.5	29	1.6	0.9	--
Trap No. 3 Before Turbo	3.5	6.4	26	0.3	0.9	--
Trap No. 3 After Turbo	3.8	9.2	28	0.4	0.9	--
Without Muffler	6.3	7.1	28	1.9	0.9	--
Trap No. 4 Before Turbo	4.1	6.4	26	0.3	0.8	--

TABLE 43. SMOKE OPACITIES FROM BUS 8296

Bus Configuration	Smoke Opacity, %, by Operating Conditions			
	Idle[a]	Snap Idle	Stall	Acceleration[b]
Baseline	0.8	35	4.2	29-37
Without Muffler	0.4	27	2.1	20-28
Trap No. 1 Before	0.3	2.0	1.2	1.2
Trap No. 1 After	0.3	2.0	2.3	0.5
Without Muffler	0.4	37	4.2	25-30
Trap No. 2 Before	0.3	1.5	0.6	2.0
Trap No. 2 After	0.3	1.0	0.3	1.0
Without Muffler	0.5	48	6.3	32-44
Trap No. 3 Before	0.2	1.0	1.4	1.5
Trap No. 3 After	0.1	0.5	0.5	0.5
Without Muffler	0.8	48	9.0	43-50
Trap No. 4 Before	0.1	1.2	2.3	2.3

[a]idle in neutral
[b]peak measured during CBD cycle

TABLE 44. ACCELERATION TIMES OF BUS 8296 ON THE DYNAMOMETER WITH AN INERTIA OF 31,000 POUNDS

Bus Configuration	Acceleration Time, second			
	0-10	0-20	0-40	0-50
Baseline	4.8	10.5	31.3	50
Without Muffler	4.3	9.8	33	54
Trap No. 1 Before	4.3	10.4	33	52
Trap No. 1 After	4.5	10.2	31	48
Without Muffler	4.0	9.5	29	48
Trap No. 2 Before	4.3	9.8	31	49
Trap No. 2 After	4.7	10.3	31	50
Without Muffler	4.4	9.4	29	46
Trap No. 3 Before	4.4	10.5	35	57
Trap No. 3 After	4.1	9.6	31	52
Without Muffler	4.3	9.5	29	48
Trap No. 4 Before	4.3	10.2	33	54

increased from 1.5 psi to 5.4 psi at 31 mph with high load. This increased backpressure caused high trap inlet and substrate temperatures similar to those observed when using two valves of air box bleed.

The bus was road tested with Trap No. 3 located after the turbocharger. Noise measurements indicated about the same levels noted with the muffler. The bus was operated on the road route, and the trap accumulated particulate. No regeneration was noted with normal operation over the road route. Two air box bleed valves were opened, but even though higher exhaust and trap temperatures were apparent, no regeneration was noted by a decrease in trap Δ p. Additional runs were made with high backpressure, and some regeneration was observed over the high speed (55 mph) portion of the route.

The bus was repositioned on the chassis dynamometer, and a controlled regeneration of Trap No. 3, located after the turbocharger, was conducted with high load during a 31 mph steady-state in combination with increased backpressure and air box bleed. These engine upset measures caused the exhaust temperature to the turbocharger to reach 700°C, while the inlet to the trap (after the turbocharger) reached 620°C. Trap substrate temperatures measured between 700 and 600°C during this steady-state condition. Recall that temperatures near 600°C are generally sufficient to cause soot oxidation without the use of a catalyst. During this regeneration operation, smoke opacity readings between 5 and 10 percent were noted immediately after closure of air box bleed valves.

The exhaust was rerouted for road evaluation of Trap No. 3 before the turbocharger. Noise measurements indicated slightly higher levels of noise from the engine cooling fan side of the bus. At the beginning of the road work, trap Δp during snap-idle measured about 58 in. H_2O. After the 10-mile road route, the Δp was about 59 in. H_2O. After another run, it was near 56 in. H_2O. After a third run, the Δp for snap-idle measured about 58 in. H_2O. Temperature and Δp data recorded over the road route indicated that some regeneration was taking place over a four-minute section of 55 mph road operation.

In addition, temperature levels similar to those noted during the 55 mph cruise condition also were briefly noted during other parts of the road route (namely, where slight road grades were encountered). It was assumed that some regeneration was taking place during these high-temperature portions of the road route, even though no definite decrease in trap Δ p could be identified because of the transient nature of the road work. Recall that these road evaluations were conducted with a passenger, driver, and equipment load of about 800 lb, and with the air conditioning off.

With Trap No. 3 located before the turbocharger, two additional road routes were run with the air conditioning on. Slightly higher exhaust and trap temperatures were noted, and some regeneration was observed on the 55 mph portion of the road route. Use of the air conditioning system was discontinued and the trap Δp measured about 58 in. H_2O. It appeared that Trap No. 3, mounted before the turbocharger, had reached a point of equilibrium on the road route.

To see if the trap Δp could be reduced over the road route, one valve for air box bleed was opened for engine upset. After WOT accelerations for performance were completed, trap Δp at snap-idle measured about 64 in. H_2O. Notably higher temperatures were obtained over the road route with one valve open for air box bleed, and partial regeneration was evident during the 55 mph portion of the run. The exhaust gases into the trap reached 550°C, and the trap substrate operated between 490 to 630°C on the 55 mph portion of the route. These temperatures were about 50°C to 60°C higher than encountered without the use of air box bleed when the trap was located before the turbocharger.

Another run of the road route was made with one valve of air box bleed. After both runs were completed, the trap Δp at snap-idle measured about 68 in. H_2O. Despite definite indications of regeneration on the road course, continued use of one valve of air box bleed apparently caused additional particulate emissions such that the trap Δp indicated a net increase in trap loading over the road route. Two more runs were conducted with no engine upset to see if trap loading would be reduced by self-regeneration. The trap Δp at snap-idle showed only a moderate increase (from 68 to 72 in. H_2O), indicating that no net regeneration occurred.

It was thought that engine upset by venting two valves of air box bleed might be sufficient to cause a significant regeneration; however, there was concern that Trap No. 3 could be damaged during experimentation with more air box bleed, because temperatures were expected to increase significantly. The bus was repositioned on the chassis dynamometer, and a controlled regeneration was conducted at 31 mph using high load and with two valves of air box bleed. Trap substrate reached 500°C when the dynamometer load was equivalent to about 75 percent of full engine load with engine upset (two valves of air box bleed). Some decline in trap Δp was observed with exhaust gases to the trap at 530°C and the trap substrate at 550°C. After 3 minutes, the trap outlet temperature stabilized to 510°C. Higher loads were run, yielding even higher temperatures. A noticeable regeneration occurred over 1 minute with a 90 percent dynamometer load at 31 mph. Trap inlet temperature was 560°C, trap substrate reached 640°C, and trap outlet reached 580°C.

When exhaust gas temperature began to fall because of reduced trap Δp, the load was increased to bring the temperature backup to near 550°C. When no further regeneration was noted, one valve for air box bleed was closed. This increased engine breathing and reduced the exhaust temperature to the trap by 90°C. Of the seven thermocouples located in and around the trap, thermocouple No. 6, located in the substrate near its outlet, indicated a sharp rise in temperature. The temperature reached 760°C in about 30 seconds.

The other air box bleed valve was closed, and the exhaust temperature to the trap fell from 480 to 440°C. Thermocouple No. 6 indicated that the temperature of the substrate stabilized briefly at 770°C, then decreased gradually to 450°C in about 1 minute. During the excursion to 770°C, the trap outlet temperature declined from 575 to 550°C. After regeneration on the dynamometer, the trap Δp during snap-idle measured 35 in. H_2O. This Δp quickly rose to about 46 in. H_2O after only brief dynamometer operation.

These results indicated that using two valves of air box bleed could cause potential "hot spots" by reducing exhaust flow to areas of the trap that may be at the necessary temperature for reaction, but which may not have sufficient exhaust gas flow to supply adequate oxygen for reaction or to carry away the heat of reaction. There was concern that these "hot spots" exist, and that it might be impossible to monitor them because of the large trap surface area and many changing variables that cause the location of the "hot spots" to move around the interior of the trap. If any area of the trap filter surface went through too great a temperature excursion (near 1000°C), damage would be likely to occur.

After controlled regeneration of Trap No. 3 on the dynamometer, the bus was returned to road work to establish temperatures which could be encountered on the road with two valves of air box bleed. Following accelerations for performance, the trap Δp during snap-idle measured 54 in. H_2O. Temperature into the trap reached 570°C during the 55 mph portion of the road route. The substrate reached 540°C, and some regeneration was observed. During the stop-to-stop portion of the route, the trap substrate temperature ranged from 380 to 410°C. The trap Δp at the end of the route measured 53 in. H_2O.

The road route was repeated with three valves of air box bleed. Following accelerations for performance, the bus was started on the road route. Exhaust gases at the trap inlet reached 620°C during the 55 mph portion. The substrate temperature climbed to 770°C. To reduce the temperature quickly, all three air box bleed valves were closed. Thermocouple No. 6 indicated a peak temperature of 840°C. Three valves of air box bleed were used later in the road route, during the stop-to-stop portion of the route, and peak exhaust gas temperatures to the trap ranged from 550 to 620°C with substrate temperatures between 400 and 500°C. Engine upset was discontinued at this point.

Checks of trap Δp after completing the road route showed 46 in. H_2O during snap-idle. A borescope inspection of the trap outlet surface indicated that the integrity of the trap was still good. No visible smoke was noted during snap-idles conducted for trap Δp measurements during the evaluations of Trap No. 3. No further evaluation of Trap No. 3 was planned.

E. Trap No. 4

Trap No. 4 was constructed using EX-47 ceramic filter substrates, catalyzed with formulation "C." The trap assembly was installed and insulated, and the exhaust was routed around the trap for dynamometer setup and emissions check without the muffler. Afterwards, exhaust was routed through Trap No. 4 in the before turbocharger position. Replicate emissions data for the bus cycle, CBD, and hot-idle operation were collected, and the values are given in Tables 40, 41, and 42. Acceleration performance and smoke emissions were similar to those observed for earlier trap evaluations, and are given in Tables 43 and 44. Trap No. 4 was expected to reduce HC and CO emissions along with particulate; however, no reductions in these gaseous emissions were noted over the test cycles run. The emission results were very similar to those obtained with Trap No. 3, considering changes noted for emissions without the muffler. As with the other catalyzed trap units evaluated in this program, no regeneration was observed over the moderately loaded test cycles used for emissions evaluation.

When emission measurements were completed, additional bus cycle and CBD operation was conducted to increase the particulate loading in the trap (snap-idle Δp of 62 in. H_2O). The bus was operated at 31 mph for regeneration, and the dynamometer load was increased to raise the exhaust gas temperature to Trap No. 4. The balance temperature, where the Δp stabilized and tended to fall off gradually, was not observed until exhaust gas temperature to the trap was 510°C and the trap substrate reached 510°C (trap outlet reached 490°C). Dynamometer load was increased to the 90 percent level to bring the exhaust gas temperature to 530°C. Substrate temperature reached 540°C, and some gradual drop in Δp was observed. At full load, the exhaust gases to the trap reached 550°C. When Trap No. 4 substrate reached 550°C, the Δp dropped at a rate of about 2 in. H_2O per minute (same rate as noted with Trap No. 2 and No. 3). After cooling, the trap Δp measured 32 in. H_2O during snap-idle, indicating that the trap was essentially clean.

Trap No. 4 was similar to the two previous catalyzed trap units, which required substrate temperatures ranging between 510 to 550°C for notable regeneration. In addition, experiments with the other units demonstrated that the before turbocharger position was the most favorable position for obtaining the high temperature exhaust gases needed for regeneration. For these reasons, no testing of Trap No. 4 after the turbocharger was planned. No road testing of Trap No. 4 was planned, because pressure and temperature data already recorded for Trap No. 2 and No. 3 were similar, and because Trap No. 4 did not appear to be much different on the basis of data already obtained.

F. Conclusion of Trap Test Work

All three catalyzed trap units met the goals of 70 percent reduction of total particulate emissions and elimination of visible smoke from the bus. All three catalyzed units exhibited similar exhaust temperature requirements for meaningful trap regeneration. This temperature range, 510 to 550°C, could be obtained on the bus by mounting the trap assembly before the turbocharger, and by operating the engine at high loads. These temperatures could also be obtained at slightly lower loads, but only with the use of engine upset (air box bleed). Engine upset was meant to reduce the air flow through the engine, causing higher-than-normal exhaust temperatures. Engine upset also increased total particulate emissions from the engine, which had to be collected in the trap. The degree of engine upset required to obtain high exhaust temperatures needed for trap regeneration was dependent on the engine load and system backpressure. The highest levels of exhaust heat were obtained during acceleration or hill climb phases of bus operation, where substantial work was done and where engine fuel usage was greatest.

It was considered unlikely that any of the catalyzed traps designed for this program could be regenerated during lightly-loaded bus operation on an inner-city service route, where only brief accelerations would be possible. Chances for obtaining the necessary balancing regenerations of the catalyzed ceramic traps evaluated in this program would be enhanced as the average exhaust temperature was increased. This higher average exhaust temperature would be expected as the engine load on the bus was increased through a combination of increased passenger load, longer accelerations, and use of higher route speeds. Additional work would be necessary to cause reliable regeneration over general engine operation by using fuel additives, adaptation of heating elements, burners, or some other means to cause regeneration of the ceramic trap assemblies. Use of electrical heating elements would entail substantial trap redesign, heating element selection/screening, and use of a larger alternator.

Based on the information obtained on the three catalyzed traps evaluated in this program, and in view of the October 31, 1986 deadline for return of the bus, field demonstration of any or all of the existing traps was considered feasible only if the in-service route periodically included high engine load operation sufficient to cause the trap to reach regeneration temperatures for about 5 out of 30 minutes of in-service operation. Engine upset might be used to increase the number of suitable routes, but without substantial in-service experimentation, it was difficult to know. In addition, durability of the trap units and their sensitivities to potential catalyst poisons are unknown. In the event no regeneration or insufficient regeneration was obtained, then a forced regeneration on a dynamometer at an SCRTD or ARB facility would be necessary. If the above restrictions were not feasible, then no demonstration of any of the three trap units evaluated in this program was recommended, and the bus was to be returned to SCRTD in the "as-received" configuration.

If a demonstration was to be performed on one or all three of the catalyzed trap units, then it was planned that the bus would be fitted with one of the available units. (replacement ceramics for Trap No. 2 were on order). Emissions characterization, similar to that performed during baseline operation, would be performed on the bus fitted with the selected trap assembly. The bus would be equipped with a tamperproof recording system and a system to cause a limited degree of engine upset when desirable. The bus would be driven back to SCRTD, with exhaust routed around the trap, for acceptance by October 31, 1986.

Based on the information and alternatives presented, further work with the catalyzed ceramic trap assemblies developed for this program was stopped by the ARB. Commitments for catalyzing and canning replacement ceramics for a duplication of Trap No. 2 were cancelled. Official notice to return the bus to SCRTD was received October 6, 1986.

The bus was restored to the "as-received" configuration. This restoration included replacing some tubing, removing air box bleed hardware, removing aftercooler bypass hardware, reinstalling the stock muffler, resetting fuel injection timing, and resetting the throttle delay. The bus was driven back to California and was accepted by SCRTD on October 23, 1986 with no major deficiencies noted. One-half of Trap No. 2 assembly was delivered to the ARB, along with Trap No. 3, for examination by interested parties. Support piping and other hardware needed for installation of the catalyzed ceramic trap was retained by SwRI along with the other half of Trap No. 2 and the Trap No. 4 assembly. Return of the bus to SCRTD marked the end of experimentation with catalyzed ceramic traps for this program. Hardware items fabricated for air box bleed experiments were forwarded to Johnson Matthey per request of the ARB.

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